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Low-Cost Feed Resources for Sustainable Dairying: Exploring Conventional, Agro-Industrial, and Non-Conventional Feeds to Optimize Nutritional Adequacy

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Abstract

This study explores the potential of cost-effective feed resources to enhance the sustainability of dairy farming by focusing on conventional, agro-industrial, and non-conventional feed alternatives. Rising feed costs remain a significant challenge =124ed5y7u-8 n dairy production, and optimizing feed efficiency is crucial for maintaining profitability and sustainability. Conventional feed resources, including roughages and pastures, provide the foundation for dairy cow diets, yet their nutritional content varies seasonally and geographically. Agro-industrial by-products, such as rice bran, wheat bran, and molasses, offer an opportunity to reduce feed costs while utilizing waste products from other agricultural sectors. Non-conventional feeds, such as aquatic plants, tree fodders, and kitchen waste, present innovative solutions for enhancing cow nutrition while reducing environmental impact. These alternative feed sources can contribute to the optimization of nutrient utilization, improving milk production, cow health, and overall farm sustainability. However, the variability in nutrient content, processing requirements, and potential anti-nutritional factors of these feeds pose challenges that must be addressed through proper management and supplementation. This study examines the prospects, challenges, and practical applications of each feed category and provides valuable insights into their role in the future of sustainable dairy farming. The findings underscore the importance of integrating diverse feed resources into dairy nutrition strategies to achieve balanced, cost-effective, and environmentally sustainable production systems.

Keywords: Agro-industrial by-products, alternative feeds, cost-effective nutrition, dairy farming sustainability, feed optimization, non-conventional feeds, roughages

INTRODUCTION

The rising cost of feed remains one of the most pressing challenges in dairy farming, contributing to a significant portion of overall production expenses. As demand for dairy products increases globally, the need for cost-effective, sustainable feeding strategies becomes paramount. Traditional feed sources, primarily roughages and pastures, have been the backbone of dairy cattle nutrition for centuries. However, these resources are not always readily available, and their quality can fluctuate due to seasonal variations and geographical constraints [1]. The dependence on these conventional feeds alone is insufficient to meet the growing nutritional demands of high-producing dairy cows. Therefore, exploring alternative feed resources has become critical for ensuring long-term sustainability in dairy farming.

Agro-industrial by-products, such as rice bran, wheat bran, and molasses, offer promising opportunities for reducing feed costs while

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maximizing the use of agricultural waste. These by-products, often discarded or underutilized, are rich in essential nutrients and can provide a cost-effective supplement to traditional feed sources [2]. Additionally, non-conventional feed resources, including aquatic plants, like Azolla and duckweed, tree fodders, and even kitchen and market waste, represent innovative and sustainable feeding solutions [3]. These feed alternatives have gained attention for their ability to improve nutrient utilization, reduce feed costs, and minimize environmental impact. Despite their potential, the variability in their nutritional content and possible anti-nutritional factors pose challenges in their integration into dairy diets.

The novelty of this study lies in its comprehensive approach to evaluating and integrating a wide range of feed alternatives from conventional, agro-industrial, and non-conventional sources. By systematically examining the benefits, limitations, and practical applications of these feeds, this research provides valuable insights into optimizing dairy cow nutrition. It also highlights the potential for utilizing waste materials and under-exploited resources, which contribute to both economic and environmental sustainability in dairy farming. The study aims to bridge the knowledge gap regarding these feed resources, offering a pathway to cost-effective, efficient, and sustainable dairy production systems.

ROUGHAGES

Rice Straw

Rice straw is an abundant and low-cost feed resource, offering substantial fiber that supports rumen function in dairy cows [4]. It is widely available in rice-producing regions and serves as a reliable roughage option. However, rice straw is low in protein and energy, necessitating supplementation with protein-rich feeds to optimize dairy cow performance and milk production.

Wheat Straw

Wheat straw is an inexpensive roughage source, providing fiber to promote rumen health and digestion. It is readily available in areas where wheat is grown. Despite its advantages, wheat straw has a low protein and energy content [5], requiring supplementation with other feed ingredients to ensure balanced nutrition for dairy cows, especially for lactating animals.

Maize Stover

Maize stover is a cost-effective roughage, rich in fiber, and commonly available in regions with maize cultivation. It supports rumen function and aids in digestion. However, maize stover has low protein and energy content, limiting its nutritional value [6]. Supplementing with protein-rich feeds or concentrates is necessary to meet the dietary requirements of dairy cows, especially during lactation.

Barley Straw

Barley straw is a cheap, fiber-rich roughage option that supports rumen function and digestion in dairy cows. It is widely available in barley-growing regions. However, barley straw's low protein content limits its nutritional value, making it necessary to provide supplementary feeds rich in protein to ensure the optimal growth, milk yield, and overall health of dairy cows.

Sorghum Stover

Sorghum stover is a high-fiber, cost-effective feed resource ideal for dry regions where sorghum is grown. It provides bulk in the diet, supporting rumen health. Despite these benefits, sorghum stover lacks sufficient protein and energy, requiring supplementation to meet the nutritional needs of dairy cows [7], especially in lactating or high-performing herds to maintain milk production.

Millet Stover

Millet stover offers a low-cost, fiber-rich feed that helps support rumen health in dairy cows. It is widely available in millet-growing regions. However, millet stover is low in protein and energy, limiting its ability to serve as a primary feed resource. Supplementation with protein-rich ingredients is essential to meet the nutritional demands of dairy cows for optimal performance.

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Sugarcane Tops

Sugarcane tops are a readily available, low-cost roughage resource for dairy cows, particularly in sugarcane-producing areas. They provide fiber to support rumen health and digestion. However, sugarcane tops are deficient in protein and energy, requiring supplementation with protein-rich feeds to ensure balanced nutrition [8]. Without adequate supplementation, milk production and cow health could be compromised.

Banana Leaves

Banana leaves are abundant in tropical areas and provide a cost-effective, fiber-rich roughage source for dairy cows. They help maintain rumen health and improve gut motility. Despite being an excellent roughage option, banana leaves lack sufficient nutritional content, especially protein [9]. Supplementation with protein-rich feeds is necessary to meet the energy and protein requirements of dairy cows.

Napier Grass

Napier grass is a highly productive, nutritious forage ideal for tropical regions, providing both fiber and moderate protein content for dairy cows. It supports rumen health and digestion. However, the protein content may not be sufficient for high-producing dairy cows, requiring supplementation with additional protein sources or concentrates to optimize milk production and cow performance [10].

Guinea Grass

Guinea grass is a drought-tolerant, fiber-rich feed resource suitable for tropical regions. It supports digestion and rumen health in dairy cows. However, its low protein content limits its ability to meet the nutritional needs of lactating cows. Supplementing with protein-rich feeds is necessary to ensure balanced nutrition, especially during periods of high milk production and growth.

Para Grass

Para grass thrives in waterlogged areas, providing a low-cost and reliable source of roughage for dairy cows. It offers adequate fiber for rumen function. Despite its benefits, Para grass has low protein and mineral content, necessitating supplementation with higher-protein feeds, such as legumes to meet the full nutritional requirements of dairy cows, particularly during lactation.

Rhodes Grass

Rhodes grass is a drought-resistant, nutritious grass that provides fiber and some protein, making it an affordable feed for dairy cows. It supports rumen health and digestion. However, the protein content of Rhodes grass is relatively low, and its feeding value may be limited. Supplementation with protein-rich sources is essential to optimize milk yield and overall cow health.

Buffel Grass

Buffel grass is a drought-tolerant, high-yielding grass that offers an affordable, sustainable roughage option for dairy cows. It is particularly useful in arid regions and provides fiber for rumen health [11]. However, its low protein and energy content make it necessary to supplement with protein-rich feeds to ensure that dairy cows' nutritional needs are met for optimal performance.

Kikuyu Grass

Kikuyu grass is a high-yielding, nutritious grass that supports rumen health and is ideal for tropical climates. It provides valuable fiber for dairy cows. Despite its benefits, Kikuyu grass has a low protein content and may not fully meet the nutritional needs of lactating cows [12]. Supplementation with protein-rich feeds is required to ensure dairy cows' optimal milk production and growth.

Elephant Grass

Elephant grass is a high-yielding, fiber-rich forage ideal for tropical and subtropical climates. It supports rumen function in dairy cows. However, elephant grass lacks sufficient protein and energy,

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requiring supplementation with protein-rich feeds or concentrates to ensure dairy cows maintain high milk production and overall health [13]. Without supplementation, its nutritional value is insufficient for lactating cows.

Oat Fodder

Oat fodder is a nutritious, fiber-rich feed that supports optimal digestion and rumen health in dairy cows. It is readily available in temperate climates and provides moderate protein content. However, the cost of growing oat fodder may limit its availability in certain areas. In addition, its nutritional profile requires balancing with supplemental feeds to meet the full nutritional needs of dairy cows.

Hybrid Sorghum

Hybrid sorghum is a high-yielding, drought-resistant feed option that provides substantial fiber for dairy cows. It grows well in arid regions and serves as a reliable roughage source. However, hybrid sorghum is low in protein and energy, meaning supplementation with higher-protein feeds or concentrates is required to ensure dairy cows meet their nutritional needs for milk production and growth.

Pearl Millet Fodder

Pearl millet fodder is a drought-tolerant, fiber-rich feed resource, ideal for regions with water scarcity [14]. It supports rumen health and digestion in dairy cows. However, like other millet-based feeds, it is low in protein and energy. Supplementing with protein-rich feeds is essential to meet the nutritional needs of dairy cows, especially during periods of lactation and growth.

Alfalfa Hay

Alfalfa hay is a high-protein, fiber-rich forage that supports dairy cow health and productivity. It provides essential nutrients that aid in milk production [15]. However, alfalfa hay is relatively expensive compared to other roughages, making it cost-prohibitive for some dairy farmers. Balancing its use with less costly feed options can help manage overall feed costs while maintaining cow performance.

Berseem

Berseem is a high-protein legume that provides excellent roughage for dairy cows. It supports growth and milk production, especially in areas with suitable growing conditions. However, Berseem's higher cost compared to other roughage sources and the need for proper irrigation and management can limit its widespread use. Supplementing with low-cost roughage options can help offset these challenges.

AGRICULTURAL BY-PRODUCTS

Maize Cobs

Maize cobs are a low-cost by-product commonly available in regions with maize cultivation. They provide valuable fiber that supports rumen function and digestion in dairy cows. However, maize cobs have limited nutritional value, being low in protein and energy [16]. Supplementation with protein-rich feeds is necessary to ensure that dairy cows receive the required nutrients for optimal milk production and growth.

Groundnut Haulms

Groundnut haulms are an affordable by-product that provides fiber and some protein, making them useful as roughage for dairy cows. They are widely available in regions where groundnuts are grown. However, groundnut haulms are low in energy and may not meet the full nutritional needs of lactating cows [17]. Supplementation with energy-rich feeds is needed to optimize dairy cow performance and milk yield.

Chickpea Haulms

Chickpea haulms are a cost-effective feed resource, offering fiber that supports rumen health in dairy cows. They are widely available in areas where chickpeas are cultivated. Despite their fiber content,

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chickpea haulms are low in protein and energy. Supplementation with additional protein and energy sources is required to meet the full nutritional requirements of dairy cows, especially in high-producing herds.

Pigeon Pea Stalks

Pigeon pea stalks are a fiber-rich by-product from pigeon pea cultivation, serving as a low-cost feed option for dairy cows. They support digestion and rumen health. However, pigeon pea stalks are low in protein and energy, limiting their nutritional value. Supplementing with protein-rich feeds, such as legumes or concentrates, is necessary to ensure dairy cows' dietary requirements are met for milk production.

Cottonseed Hulls

Cottonseed hulls are a low-cost by-product from cotton production, providing fiber for dairy cows. They help maintain rumen health and improve digestion. Despite their benefits, cottonseed hulls are low in protein and energy [18]. To meet the nutritional needs of dairy cows, especially lactating cows, cottonseed hulls should be supplemented with protein-rich feeds or concentrates to optimize performance and milk yield.

Sunflower Husks

Sunflower husks are a readily available, low-cost by-product that provides fiber for dairy cows. They support rumen health and aid in digestion. However, sunflower husks are low in protein and energy, limiting their ability to meet the full nutritional needs of dairy cows. Supplementation with protein-rich feeds is essential to optimize milk production, particularly in lactating or high-producing herds.

Soybean Husks

Soybean husks are an affordable by-product offering fiber to support rumen function in dairy cows. They are commonly available in regions where soybeans are processed. However, soybean husks have a low protein and energy content, which necessitates supplementation with other protein-rich or energy-dense feeds to ensure that dairy cows maintain high performance and milk production during lactation.

Wheat Bran

Wheat bran is a cost-effective by-product, rich in fiber and some protein, making it a valuable roughage option for dairy cows. It supports digestion and rumen health. However, wheat bran may be low in energy compared to other concentrates. Supplementing with additional energy-rich feeds or grains is necessary to meet the full nutritional requirements of dairy cows for optimal growth and milk production.

Rice Bran

Rice bran is an affordable by-product rich in fiber, vitamins, and minerals, providing valuable roughage for dairy cows. It supports rumen function and digestion. However, rice bran is relatively low in protein and energy, limiting its nutritional value. Supplementing rice bran with protein-rich feeds or concentrates is necessary to ensure dairy cows meet their dietary requirements, particularly for high-producing animals.

Maize Bran

Maize bran is a low-cost, fiber-rich by-product from maize milling, offering an affordable feed option for dairy cows. It supports rumen health and digestion [19]. However, maize bran is low in protein and energy, which can limit its effectiveness as a sole feed. Supplementing with protein-rich or energy-dense ingredients is crucial to ensure dairy cows receive balanced nutrition for optimal milk production and growth.

Barley Bran

Barley bran is an inexpensive, fiber-rich by-product that helps support rumen health in dairy cows. It provides essential roughage, contributing to proper digestion. However, barley bran is relatively low in

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protein and energy, meaning it should be supplemented with higher-protein feeds to meet the nutritional needs of dairy cows. Without supplementation, it may not sustain high milk production or growth.

Millet Bran

Millet bran is a cost-effective by-product that provides fiber to support rumen health and digestion in dairy cows. It is widely available in millet-growing regions. However, millet bran is low in protein and energy, requiring supplementation with protein-rich feeds to meet the dietary requirements of dairy cows, particularly in lactating herds where protein and energy intake is crucial for milk yield.

Sorghum Bran

Sorghum bran is an affordable by-product, rich in fiber and some protein, which supports rumen health in dairy cows. It is commonly available in regions where sorghum is grown. However, sorghum bran's protein content may not be sufficient for lactating or high-performing cows. Supplementation with protein-rich feeds or concentrates is necessary to meet dairy cows' nutritional needs for optimal milk production.

Sugar Beet Pulp

Sugar beet pulp is a valuable by-product providing fiber and some energy, making it a suitable roughage for dairy cows. It supports digestion and rumen health. However, sugar beet pulp is low in protein and should be supplemented with protein-rich feeds, such as legumes or concentrates, to ensure balanced nutrition. Its high moisture content may also limit its storage and handling in some areas.

Cane Bagasse

Cane bagasse is a fibrous by-product from sugarcane processing that serves as an affordable feed option for dairy cows. It provides bulk in the diet, supporting rumen health. However, cane bagasse has low protein and energy content, making it necessary to supplement with protein and energy-rich feeds to meet the nutritional needs of dairy cows and optimize milk production and performance [20].

Molasses

Molasses is a by-product from sugar production, offering a concentrated energy source for dairy cows. It helps enhance feed intake and supports rumen fermentation. However, molasses is low in protein, so it must be used in conjunction with protein-rich feeds to ensure a balanced diet [21]. Its high sugar content should be monitored to prevent overconsumption, which could lead to metabolic issues.

Cassava Peels

Cassava peels are an underutilized by-product that provides fiber to support rumen function in dairy cows. They are commonly available in areas where cassava is processed. However, cassava peels have a low protein and energy content, limiting their effectiveness as a sole feed source [22]. Supplementing with protein-rich feeds and energy-dense concentrates is necessary to meet the full nutritional needs of dairy cows.

Yam Peels

Yam peels are a low-cost by-product that can provide fiber for dairy cows, helping to support rumen function and digestion. They are readily available in areas where yam is cultivated. However, yam peels are low in protein and energy, which means they need to be supplemented with protein-rich feeds to meet the nutritional requirements of dairy cows, especially for lactating animals.

Potato Peels

Potato peels are an affordable by-product that can provide fiber for dairy cows. They help support rumen health and aid in digestion. However, potato peels are low in protein and energy and may not meet the full nutritional needs of lactating cows. Supplementation with protein-rich feeds or concentrates is necessary to ensure dairy cows maintain high milk production and overall health.

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Carrot Tops

Carrot tops are a nutritious by-product that provides fiber and some protein for dairy cows. They are particularly useful for enhancing rumen function and supporting digestion. However, carrot tops are low in energy, and their nutritional content may not be sufficient for lactating or high-producing cows. Supplementing with protein and energy-rich feeds is necessary to meet the nutritional requirements of dairy cows.

TREE FODDERS

Leucaena Leaves

Leucaena leaves are a high-protein, low-cost tree fodder commonly used in dairy farming. They provide a good source of digestible nutrients and support rumen function in dairy cows. However, their high tannin content can reduce protein digestibility if fed excessively [23]. Proper management of intake is needed, and they should be supplemented with other feed ingredients to ensure a balanced diet for optimal production.

Gliricidia Leaves

Gliricidia leaves are a nutritious tree fodder providing protein, fiber, and essential minerals. They support rumen health and enhance digestion in dairy cows. However, the presence of certain anti-nutritional factors may limit their nutritional value if overfed [24]. Careful monitoring of feeding quantities and supplementation with other protein and energy-rich feeds is essential to avoid potential negative impacts on dairy cow performance.

Sesbania Leaves

Sesbania leaves are a valuable tree fodder rich in protein, which supports the growth and milk production of dairy cows. They improve rumen fermentation and digestion. However, their high fiber content can make them less palatable, and they may cause digestive upset if fed in large quantities. Supplementing with other energy-rich feeds ensures that dairy cows receive a balanced nutrient intake.

Moringa Leaves

Moringa leaves are a highly nutritious tree fodder, rich in protein, vitamins, and minerals, making them an excellent supplement to dairy cow diets. They enhance milk yield and overall health [25]. However, the high nutrient density may lead to imbalances if fed in excess. To avoid nutritional imbalances, moringa leaves should be used in combination with other forages and concentrates to ensure a balanced diet.

Acacia Leaves

Acacia leaves are a valuable protein source for dairy cows, offering essential nutrients that support growth and milk production. They are especially useful in regions where other feed resources are scarce. However, acacia leaves can contain tannins and other compounds that limit protein digestibility and palatability [26]. Proper inclusion rates and careful supplementation are necessary to maximize their benefits in dairy nutrition.

Subabul Leaves

Subabul leaves are a cost-effective, protein-rich tree fodder that supports the nutritional needs of dairy cows. They are known for promoting rumen health and increasing milk production. However, excessive consumption of subabul leaves may lead to digestive issues due to their high fiber content [27]. Balancing their inclusion with other protein and energy-rich feeds is essential to optimize cow performance and maintain health.

Neem Leaves

Neem leaves are a traditional tree fodder offering medicinal properties, along with moderate nutritional content for dairy cows. They support rumen health and are believed to have anti-parasitic effects. However, neem leaves contain certain compounds that may interfere with nutrient absorption

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and digestion if overfed. Supplementing with other forages and maintaining controlled intake ensures that dairy cows benefit without any adverse effects.

Mulberry Leaves

Mulberry leaves are a highly nutritious feed resource for dairy cows, providing a good balance of protein, vitamins, and minerals. They support rumen function, digestion, and milk production. However, their availability is seasonal, and they may not always be abundant for consistent use. To optimize their inclusion, mulberry leaves should be stored and combined with other forage resources to maintain a balanced diet for dairy cows.

Jackfruit Leaves

Jackfruit leaves are a nutritious tree fodder that provides fiber and protein for dairy cows. They support rumen health and contribute to overall cow well-being. However, jackfruit leaves can be fibrous and may be less palatable for dairy cows if fed in excess. Balancing their use with other tree fodders and feeds is necessary to prevent dietary imbalances and ensure optimal production.

Erythrina Leaves

Erythrina leaves are a high-protein tree fodder that supports rumen health and enhances digestion in dairy cows. They have been shown to improve milk yield and overall performance. However, erythrina leaves may contain compounds that could reduce palatability or limit protein digestibility when overfed. Proper management and supplementation with other feeds are necessary to maintain a balanced and effective diet for dairy cows.

LEGUMINOUS FODDERS

Cowpea Fodder

Cowpea fodder is a highly nutritious leguminous feed, rich in protein and fiber, supporting the growth and milk production of dairy cows [28]. It promotes rumen health and enhances digestion. However, cowpea fodder can be low in energy and may require supplementation with energy-rich feeds to meet the full nutritional needs of high-producing dairy cows, especially during lactation.

Horse Gram Fodder

Horse gram fodder is a valuable source of protein and fiber, which supports dairy cow growth and milk yield. It is particularly useful in regions with limited feed resources. However, horse gram fodder is low in energy and can be less palatable due to its high fiber content. Supplementing with other energy-dense feeds is necessary to optimize dairy cow performance.

Mung Bean Fodder

Mung bean fodder is an affordable, protein-rich leguminous feed that supports the health and performance of dairy cows. It improves rumen function and digestion, promoting better nutrient absorption. However, mung bean fodder may lack sufficient energy to meet the needs of lactating cows. Supplementing with energy-rich concentrates ensures balanced nutrition and supports high milk production.

Cluster Bean Fodder

Cluster bean fodder is a nutritious legume providing protein and fiber for dairy cows. It supports rumen health, improves digestion, and enhances milk production [29]. However, cluster bean fodder can be high in fiber, which may limit its energy content. Supplementation with energy-dense feeds or grains is essential to ensure dairy cows receive the necessary energy for optimal production and growth.

Green Gram Fodder

Green gram fodder is a valuable leguminous feed for dairy cows, offering a good balance of protein and fiber, which supports digestion and rumen health. It contributes to increased milk yield and cow health. However, green gram fodder may be low in energy, necessitating supplementation with energy-rich feeds, particularly for lactating cows that require higher energy intake for milk production.

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Velvet Bean Fodder

Velvet bean fodder is a highly nutritious legume that provides protein, fiber, and essential minerals to dairy cows. It promotes rumen health and supports improved digestion. However, velvet bean fodder contains anti-nutritional factors, such as tannins, that may reduce protein digestibility if fed excessively [30]. Proper management and supplementation with other feeds are required to optimize the nutritional benefits for dairy cows.

NON-CONVENTIONAL FEEDS

Brewery Waste

Brewery waste is a high-protein by-product from the brewing industry, offering a cost-effective feed for dairy cows. It provides essential nutrients for growth and milk production [31]. However, the high moisture content can limit its shelf life and may require drying for storage. Careful management of intake is necessary to avoid digestive disturbances and ensure proper nutrient balance for dairy cows.

Distiller's Grains

Distiller's grains are a valuable by-product from ethanol production, rich in protein and fiber, which supports rumen health and milk production in dairy cows [32]. However, their high phosphorus content may lead to mineral imbalances if not properly balanced with other feed ingredients. Supplementation with energy-rich feeds and proper management of mineral intake is essential for optimizing dairy cow performance.

Pressed Sugarcane Bagasse

Pressed sugarcane bagasse is a fibrous by-product from sugarcane processing, offering a source of roughage for dairy cows. It supports rumen function and enhances digestion. However, bagasse is low in protein and energy, requiring supplementation with higher-quality feeds to meet the nutritional needs of lactating cows. Its high fiber content may also limit intake if not combined with more palatable feeds.

Fruit Pulp Residues

Fruit pulp residues are a nutritious by-product from fruit processing, providing essential sugars, fiber, and vitamins for dairy cows. They support overall cow health and milk production [33]. However, fruit pulp residues can be low in protein and energy, which may limit their effectiveness as a sole feed source. Supplementation with protein-rich feeds ensures a balanced and nutritionally complete diet for dairy cows.

Coconut Meal

Coconut meal is a high-protein feed by-product from the coconut oil industry, offering a valuable source of nutrition for dairy cows. It provides essential amino acids and supports milk production. However, coconut meal has a relatively low fiber content and may lack sufficient energy for lactating cows. Supplementing with energy-rich feeds is necessary to meet the complete nutritional needs of high-producing cows.

Palm Kernel Meal

Palm kernel meal is a by-product from palm oil extraction, rich in protein and fiber, making it a valuable feed resource for dairy cows. It supports rumen health and milk production [34]. However, palm kernel meal may be low in certain essential nutrients, like minerals, and careful management of the diet is needed to ensure cows receive a well-rounded nutrient intake, particularly during lactation.

Rubber Seed Meal

Rubber seed meal is a non-conventional feed resource that provides protein and fiber for dairy cows. It supports rumen health and overall performance. However, rubber seed meal contains certain anti-nutritional factors, such as cyanogenic compounds, that can interfere with nutrient absorption [35]. Proper processing and moderation in inclusion rates are necessary to ensure safe and effective use in dairy cow diets.

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Coffee Pulp

Coffee pulp is a by-product from coffee processing, offering a source of fiber and some nutrients for dairy cows. It supports rumen function and provides roughage for digestion [36]. However, coffee pulp is low in protein and energy, requiring supplementation with more nutrient-dense feeds to meet the nutritional needs of lactating cows. Its high fiber content may also limit intake if not properly balanced.

Cocoa Pod Husks

Cocoa pod husks are a fibrous by-product from cocoa processing, providing a source of roughage for dairy cows. They support rumen health and improve digestion. However, cocoa pod husks are low in protein and energy, which may limit their ability to meet the full nutritional requirements of dairy cows. Supplementing with protein and energy-rich feeds ensures balanced nutrition for optimal milk production.

Tamarind Seed Meal

Tamarind seed meal is a protein-rich by-product from tamarind processing, offering valuable nutrients for dairy cows. It supports growth, milk production, and rumen health [37]. However, tamarind seed meal contains certain anti-nutritional factors that may reduce protein digestibility. Proper processing and inclusion rates are essential to maximize its nutritional benefits and minimize any negative effects on cow health and performance.

Mango Kernel Meal

Mango kernel meal is a by-product from mango processing, providing protein and fiber for dairy cows. It supports rumen function and overall cow health [38]. However, mango kernel meal may lack sufficient energy to support high milk production. Supplementing with energy-rich feeds ensures dairy cows receive a balanced diet, especially during lactation when higher energy intake is required to maintain milk yield.

Groundnut Shells

Groundnut shells are a low-cost, fibrous by-product from peanut processing, offering roughage for dairy cows. They support rumen function and digestion [39]. However, groundnut shells are low in protein and energy, requiring supplementation with protein-rich and energy-dense feeds to meet the nutritional needs of dairy cows. Their high fiber content may limit palatability and intake, making them suitable only as a roughage source.

Cashew Nutshell Meal

Cashew nutshell meal is a by-product from cashew processing, offering a source of protein and fiber for dairy cows. It supports rumen health and overall cow performance [40]. However, cashew nutshell meal contains certain anti-nutritional factors, such as tannins, that may reduce nutrient digestibility and palatability. Proper processing and moderation in inclusion rates are necessary to optimize its use in dairy cow diets.

Tea Waste

Tea waste is a by-product from tea processing, offering a source of fiber and some nutrients for dairy cows. It supports rumen function and provides roughage for digestion [41]. However, tea waste is low in protein and energy, requiring supplementation with other protein-rich and energy-dense feeds to ensure a balanced diet for dairy cows, especially during lactation when nutritional demands are higher.

GRAINS AND SEEDS

Broken Rice

Broken rice is a cost-effective by-product from rice milling, providing a source of energy and some protein for dairy cows. It supports milk production and overall cow health [42]. However, broken rice lacks sufficient fiber and essential nutrients, which may limit its effectiveness as a sole feed. Supplementing with fiber-rich feeds and protein sources ensures a well-rounded diet and improved cow performance.

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Damaged Wheat

Damaged wheat is a low-cost by-product from wheat milling, offering a source of carbohydrates and some protein for dairy cows. It supports milk production and rumen function. However, damaged wheat may have reduced nutrient quality due to its degradation, leading to lower digestibility. Supplementing with high-quality protein and fiber-rich feeds ensures a balanced and nutritious diet for dairy cows.

Millet Screenings

Millet screenings are a by-product from millet processing, offering fiber and some protein for dairy cows. They support rumen function and digestion. However, millet screenings may contain impurities and reduced nutritional quality, which can limit their usefulness as a primary feed source. Supplementing with protein-rich and energy-dense feeds ensures a balanced diet and optimizes dairy cow performance.

Sorghum Screenings

Sorghum screenings are a by-product from sorghum milling, providing fiber and carbohydrates for dairy cows. They support rumen health and improve digestion. However, sorghum screenings may contain damaged kernels and other contaminants, reducing their overall nutritional value. Careful processing and supplementation with protein and energy-rich feeds are necessary to ensure dairy cows receive a balanced and complete diet.

Barley Screenings

Barley screenings are a by-product from barley processing, providing a source of fiber and carbohydrates for dairy cows. They support rumen health and digestion. However, barley screenings may contain low-quality grains and contaminants, reducing their nutritional value. Supplementing with high-quality protein sources and energy-rich feeds ensures a well-balanced diet and supports optimal dairy cow performance.

Maize Screenings

Maize screenings are a by-product from maize milling, offering fiber, carbohydrates, and some protein for dairy cows. They support rumen function and improve digestion. However, maize screenings may contain broken kernels and contaminants, which can lower their nutritional quality. Supplementing with higher-quality feeds and protein sources ensures a balanced diet and enhances the production and health of dairy cows.

Cottonseed Meal

Cottonseed meal is a by-product from cotton oil extraction, offering a high-protein feed source for dairy cows. It supports milk production and overall cow health [43]. However, cottonseed meal contains gossypol, a toxin that can be harmful in large quantities. Proper processing and controlled feeding are necessary to ensure safety and optimize the nutritional benefits of cottonseed meal in dairy cow diets.

Sunflower Meal

Sunflower meal is a by-product from sunflower oil extraction, rich in protein and fiber, supporting the growth and milk production of dairy cows. It promotes rumen health and enhances digestion [44]. However, sunflower meal may be low in certain amino acids and may require supplementation with other protein sources to ensure that dairy cows receive a balanced and nutritionally complete diet.

Mustard Seed Meal

Mustard seed meal is a protein-rich by-product from mustard oil extraction, providing essential nutrients for dairy cows. It supports growth, milk production, and rumen health. However, mustard seed meal contains glucosinolates, which can reduce feed intake and interfere with iodine metabolism in cows if fed in large quantities [45]. Moderation in inclusion rates is necessary to avoid potential negative effects on cow health.

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Linseed Meal

Linseed meal is a high-protein by-product from linseed oil extraction, providing essential amino acids and fiber for dairy cows. It supports milk production, improves rumen health, and enhances overall cow performance. However, linseed meal may be low in certain essential nutrients, like minerals, requiring supplementation with other feeds to ensure a well-balanced diet that meets the nutritional needs of lactating cows.

PASTURE-BASED FEEDS

Pasture Grasses

Pasture grasses are a primary source of nutrition for dairy cows, providing fiber, carbohydrates, and some protein. They support rumen health and digestion, enhancing overall cow performance [46]. However, the nutrient content of pasture grasses can vary depending on season and management practices. Supplementing with additional protein or energy-rich feeds may be necessary to meet the nutritional needs of high-producing cows.

Natural Herbage

Natural herbage, consisting of wild plants and grasses, offers essential nutrients for dairy cows, including fiber and some protein. It supports rumen function and overall cow health. However, the quality and nutrient content of natural herbage can fluctuate due to environmental factors. Proper management and supplementation may be needed to ensure balanced nutrition and meet the full dietary requirements of lactating cows.

Forest Shrubs

Forest shrubs can serve as a valuable source of nutrition for dairy cows, providing fiber, protein, and essential minerals. These shrubs can support digestion and rumen health [47]. However, their nutrient content may be less predictable compared to cultivated forage. Careful selection and supplementation with other feed sources are necessary to ensure that dairy cows receive a balanced and complete diet throughout the year.

Native Legumes

Native legumes offer a rich source of protein and fiber, benefiting the rumen health and milk production of dairy cows. They help improve nutrient utilization and support overall cow performance [47]. However, the availability and nutrient content of native legumes can vary depending on the region and seasonal factors. Supplementation with additional energy or fiber may be required to optimize dairy cow performance and health.

KITCHEN AND MARKET WASTES

Vegetable Market Residues

Vegetable market residues, such as peels, stems, and leaves, provide a low-cost source of fiber, vitamins, and some minerals for dairy cows. They support rumen function and digestion [48]. However, vegetable market residues may be low in protein and energy, which can limit their nutritional value. Supplementing with protein and energy-rich feeds is necessary to ensure balanced nutrition for dairy cows.

Fruit Market Residues

Fruit market residues, including peels, cores, and discarded fruits, offer a source of sugars, fiber, and some vitamins for dairy cows [48]. They promote digestion and rumen health. However, fruit market residues may lack sufficient protein and energy for lactating cows. Supplementing with protein-rich and energy-dense feeds is essential to meet the full nutritional needs of dairy cows, particularly during peak milk production.

Kitchen Waste

Kitchen waste, such as vegetable scraps, grains, and leftover food, can be a cost-effective feed source for dairy cows. It provides a variety of nutrients, including carbohydrates and fiber [49]. However,

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kitchen waste may contain high levels of salt, fats, or spices that are not ideal for cow health. Proper sorting and moderation are necessary to ensure the safety and nutritional quality of the feed.

Bakery Waste

Bakery waste, including stale bread, cakes, and other baked goods, can serve as a low-cost source of carbohydrates for dairy cows. It supports energy intake and rumen function [50]. However, bakery waste is often high in sugars and may be low in protein, requiring supplementation with other feed ingredients to ensure balanced nutrition. Excessive intake can also lead to digestive disturbances if not managed carefully.

Fish Market Residues

Fish market residues, including fish heads, bones, and offal, provide a source of protein and essential fatty acids for dairy cows. They support growth, milk production, and overall cow health. However, fish market residues may have high levels of salt or other compounds that could affect cow health if fed in excess. Proper processing and moderation are key to safely incorporating fish market residues into dairy cow diets.

OTHER UNCONVENTIONAL SOURCES

Azolla

Azolla is a water fern that provides a rich source of protein, fiber, and essential nutrients for dairy cows. It promotes rumen health and supports milk production [51]. However, Azolla's availability is limited by water quality and climate conditions. Careful management is needed to ensure it is safe for feeding, as excess moisture may affect cow digestion and nutritional intake.

Duckweed

Duckweed is a fast-growing aquatic plant rich in protein, fiber, and essential amino acids, making it a nutritious feed for dairy cows. It supports milk production and overall cow health [52]. However, the availability of duckweed can be influenced by water conditions, and excess feeding may lead to imbalances in cow diets. Supplementing with other feeds ensures balanced nutrition and optimal performance.

Water Hyacinth

Water hyacinth is an aquatic plant offering fiber and some protein for dairy cows. It supports rumen function and digestion. However, water hyacinth is often considered an invasive species, making its availability and sustainability unpredictable. Furthermore, it may contain toxins or contaminants, necessitating proper management and processing to ensure safe inclusion in dairy cow diets without compromising health or performance.

Algae-Based Feeds

Algae-based feeds, particularly spirulina and chlorella, are rich in protein, essential fatty acids, and micronutrients. They can improve milk production and overall cow health [53]. However, algae-based feeds are expensive to produce, which limits their widespread adoption. Additionally, sourcing high-quality algae and ensuring proper feeding rates are essential for maximizing nutritional benefits while avoiding overconsumption or negative effects on cow health.

Sweet Potato Vines

Sweet potato vines are a nutritious feed for dairy cows, providing fiber, protein, and vitamins. They support digestion, milk production, and overall cow health. However, sweet potato vines may be low in energy compared to other forages, requiring supplementation with energy-rich feeds for lactating cows. Proper harvesting and storage practices are important to maintain their nutritional quality and ensure safety for cow consumption.

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Turnip Tops

Turnip tops are an excellent source of fiber and essential vitamins for dairy cows, supporting rumen health and digestion. They can enhance milk production, particularly during times when other forages are scarce. However, turnip tops may be low in protein and energy, necessitating supplementation with other protein or energy sources. Excessive feeding of turnip tops may also lead to digestive disturbances.

Beet Tops

Beet tops provide fiber, minerals, and some protein for dairy cows, supporting rumen health and overall cow performance. They can be a valuable addition to the diet, particularly when other forage options are limited. However, beet tops are low in energy and may require supplementation with higher-energy feeds to ensure lactating cows meet their nutritional requirements. Proper storage is essential to avoid spoilage.

Cabbage Leaves

Cabbage leaves are a good source of fiber, vitamins, and minerals, supporting rumen health and cow digestion. They can help improve milk production and overall cow health. However, cabbage leaves are low in protein and energy, requiring supplementation with other protein or energy-rich feeds. Overfeeding cabbage leaves can also lead to digestive issues, so moderation and proper balance with other feeds are necessary [54].

Pineapple Peelings

Pineapple peelings are a good source of fiber and some carbohydrates for dairy cows. They promote digestion and rumen health, contributing to overall cow performance. However, pineapple peelings are low in protein and may contain high levels of sugar, which could lead to digestive disturbances if fed in excess. Careful management and supplementation with balanced feeds are essential to meet the nutritional needs of dairy cows.

Papaya Peelings

Papaya peelings are rich in fiber, vitamins, and enzymes that can aid in digestion and support rumen health [55]. They can be a useful supplement to a dairy cow's diet, particularly when other feeds are limited. However, papaya peelings are low in protein and energy, requiring supplementation with other feeds to meet nutritional needs. Excessive feeding of papaya peelings may lead to digestive disturbances or nutrient imbalances.

Citrus Pulp

Citrus pulp is a by-product from citrus juice production, providing a source of fiber and carbohydrates for dairy cows. It supports rumen function and milk production [33]. However, citrus pulp can be high in acidity, which may affect cow health if fed in large amounts. Proper balancing with other feed ingredients and careful management are necessary to ensure optimal nutrient intake and avoid digestive issues.

CONCLUSIONS

Integrating cost-effective feed resources from conventional, agro-industrial, and non-conventional sources offers significant potential to enhance sustainability and profitability in dairy farming. While traditional feeds remain essential, the inclusion of agro-industrial by-products and innovative non-conventional feeds can reduce dependency on expensive, conventional resources. These alternative feeds can improve nutrient utilization, boost milk production, and reduce environmental impact. However, challenges related to their nutritional variability and processing requirements must be addressed through careful management and supplementation. This study emphasizes the importance of diversifying feed strategies and presents a comprehensive framework for optimizing dairy cow nutrition, ultimately contributing to the development of more sustainable and economically viable dairy farming systems.

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Future Directions

Future research should focus on further optimizing the nutritional value and safety of alternative feed resources, particularly non-conventional feeds, such as aquatic plants, tree fodders, and agro-industrial by-products. Investigating the long-term effects of these feeds on dairy cow health, productivity, and milk quality will be essential for ensuring their sustainable integration into commercial farming systems. Additionally, developing cost-effective processing techniques for these feeds can enhance their digestibility and nutrient bioavailability. Further studies are needed to explore the potential of waste-to-feed systems, leveraging agricultural and food industry waste to minimize environmental impact and reduce feed costs. Collaborative efforts between farmers, researchers, and policymakers will be critical to addressing the regulatory and logistical challenges associated with incorporating alternative feeds on a large scale. Finally, precision feeding technologies should be explored to tailor feed formulations to specific herd requirements, optimizing both economic and environmental outcomes in dairy farming.

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