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Precision of dairy farming: navigating challenges and seizing opportunities for sustainable dairy production in Africa

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Precision Dairy Farming encompasses applying sophisticated technologies and data-centric methodologies to enhance the efficiency, productivity, and sustainability of dairy production. The objectives of this review focus on the precision of dairy farming; exploring the role of Precision Dairy Farming in transforming Africa's dairy sector, navigating challenges that hinder the adoption of Precision Dairy Farming in Africa, and seizing the opportunities that can be leveraged for sustainable growth in dairy farming. Precision Dairy Farming technologies include wearable sensors, automated milking systems, precision feeding systems (automated dispensers), automated environmental monitoring and cooling systems, milk analyzers and somatic cell counters, geospatial tools and GPS-Enabled Grazing Management, mobile apps for farm management and data analysis. According to different research results this technology adoption led to a 30% increase in milk yield, a 25% reduction in feed costs, and a 20% decrease in veterinary expenses. Also, it is important to improve animal health monitoring, enhance decision-making, reduce workloads, and enhance financial security. The precision of Dairy farming in Africa faces a range of economic, social, and environmental challenges that limit its growth potential, despite significant expansion opportunities. These challenges can be due to the high cost of technology, limited access to finance, infrastructural limitations, low digital literacy and limited training for farmers, data collection and management challenges, lack of adapted Precision Dairy Farming technologies for African conditions and policy and market Constraints making it hard for small farmers to adopt new tools and improve their productivity. Precision dairy farming have different opportunity such as, improving Animal health and welfare, empowering smallholder farmers with digital and mobile solutions, supporting economic growth and rural livelihoods, meeting the growing demand for dairy Products, driving sustainability and environmental protection, enhancing public-private partnerships and strengthening dairy market and supply chain resilience. By embracing Precision Dairy Farming technologies, investing in education, enhancing cooperative structures, improving market access, and supporting policy frameworks, stakeholders can collectively transform the dairy sector into a sustainable and resilient industry.

KEYWORDS

challenge, dairy, opportunity, precision, sustainable

1 Introduction

Dairy production in Africa constitutes a fundamental component in the realms of economic stability, food security, and cultural identity. It serves as a significant source of nutrition and income for many communities, and contributing to employment opportunities. Dairy farming is a vital for generating income and employment for millions of people in Africa (Tagba et al., 2024). Its products are a key source of essential nutrients, contributing to improved health and nutrition in (Mihret et al., 2017). Furthermore, it possesses significant social and cultural importance, particularly among pastoral communities, where it is deeply embedded in traditional practices and dietary habits (Mattiello et al., 2018).

Precision Dairy Farming is a transformative approach to dairy farm management that integrates advanced technology and data-driven tools to monitor and manage individual animals. By collecting detailed data on factors such as daily milk yield, milk composition (fat, protein, and somatic cell count), and animal behavior, farmers can improve both animal welfare and farm profitability. Technologies used in Precision Dairy Farming include pedometers, automatic temperature recorders, milk conductivity indicators, and estrus detection monitors, which provide real-time insights into animal health and reproductive status (Hostiou et al., 2017; Tutkun, 2023) For instance, systems like the Livestock Internet of things simplify the data collection and analysis process, allowing for more efficient decision-making and enhanced farm operations (Kassab et al., 2024).

Precision dairy farming represents an innovative approach to the administration of dairy farms. It uses for producers in making informed decisions regarding to their cow. This can include monitoring the health of cows, tracking milk production, and managing feeding schedules (Kaur et al., 2023). Automated systems integrate data from a variety of sensors to facilitate to assessments of cattle behavior and the environmental conditions within the barn, thereby contributing to thorough health evaluations (Leliveld et al., 2024). It is imperative to optimize the utilization of resources, reduce labor expenditures, and advocate for sustainable agricultural practices by ensuring that the requirements of each cattle are addressed efficiently (Wadsworth et al., 2015).

Precision Dairy Farming represents a significant advancement in farming technology, offering a transformative approach to sustainable, productive, and resilient dairy farming in Africa (Aune et al., 2017). For dairy farmers, this technological approach mitigates critical challenges, such as limited productivity and environmental sustainability (Fouad et al., 2021; Marwa et al., 2020). Precision Dairy Farming in Africa faces several barriers, Infrastructure limitations, Limited Access of Finance, low digital literacy, particularly in rural areas; hinder the deployment of advanced technologies (Ncube, 2018). These hurdles underscore the need for tailored interventions, including policy support, training programs, and financial incentives, to bridge the gap between potential and practice (Becerra-Encinales et al., 2024). By addressing the barriers and promoting equitable access to Precision Dairy Farming technologies, Africa can achieve a sustainable and resilient dairy sector, contributing to regional food security and economic development. Despite the recognized potential of precision dairy farming to improve milk yields, reduce feed costs, and promote sustainable practices, its adoption and implementation in Africa remain limited. The purpose of this review on the precision of dairy farms in Africa is to identify problems, find solutions, improve farmer's income, ensure food security, promote sustainability, and encourage innovation in data-driven approach. This review focuses on the precision of dairy farming, the challenges and potential opportunities associated with sustainable dairy production in Africa.

2 Importance of precision of dairy farming in Africa

The precision of dairy farming practices is essential for enhancing the productivity, health, and welfare of dairy cattle while concurrently minimizing environmental repercussions and enhancing economic efficiency (Kaur, 2024; Kumar et al., 2024). It has the capacity to elevate rural incomes and fortify food security, thereby promoting dietary diversity and resilience among smallholder farmers (Kihoro et al., 2024). The integration of mobile technology supports real-time decision-making, further improving sustainability in dairy farming (Bhanuwanti et al., 2024). In Kenya, interventions like improved herd management and feed strategies could close substantial yield gaps (39-49%) in dairy systems, potentially reducing GHG emission intensities by 6.5% to 27.4% (Graham et al., 2024). Precision dairy farming promotes the efficient utilization of resources, thereby reducing soil degradation and enhancing ecosystem health (Tagba et al., 2024). The increase in milk production empowers farmers to diversify into value-added products such as yogurt and cheese, thus creating additional revenue streams (Makoni et al., 2014).

Smallholders are often organized into cooperatives or producer groups. PDF strengthens these collectives by enabling shared access to technology, knowledge, and resources. With tools like health monitoring sensors, automated milking systems, and feed optimization, farmers can increase milk yield and quality. By equipping farmers with pertinent data, tools, and training, initiatives such as precision dairy farming enhance their decision-making capabilities, leading to improved agricultural practices and community development. Training programs significantly bolster farmers' knowledge and skills, thereby fostering a culture of perpetual learning (Pandey et al., 2024). Digital technologies, including block chain and sensor technologies can enhance transparency and efficiency within supply chains, effectively addressing challenges such as exploitation and financial exclusion (Quayson et al., 2020). Cooperative models facilitate knowledge sharing and collective ownership, thereby strengthening communal ties and enhancing social capital (Firmansyah et al., 2024). Initiatives that prioritize the empowerment of women in dairy farming contribute to increased productivity and improved family well-being, underscoring the significance of gender inclusivity within agricultural practices (Pandey et al., 2024). Precision Dairy farm system visual presentation describe in Figure 1.

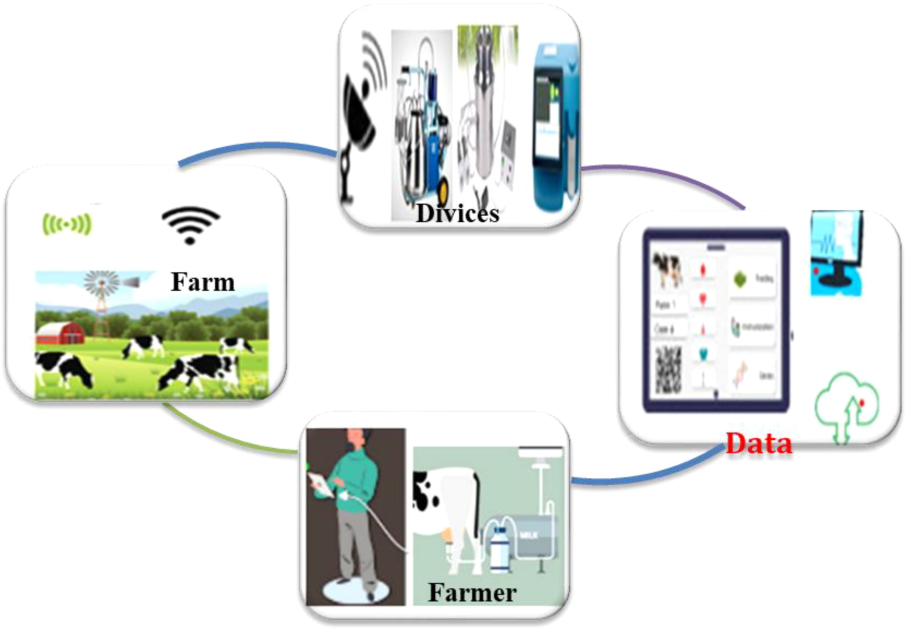

FIGURE 1
Precision dairy farming.

3 Challenges for precision of dairy farming in Africa

Precision of Dairy farming in Africa faces a range of economic, social, and environmental challenges that limit its growth potential, despite significant opportunities for expansion.

3.1 High cost of technology

The high cost of technology significantly hinders the adoption of dairy technology, particularly among smallholder farmers (Bewlwey, 2010). These technologies, such as automated milking systems, wearable animal sensors, robotic feeding systems, and data management software, require substantial initial investment (Naji et al., 2020; Mhlanga and Ndhlovu, 2023). Most this equipment is manufactured in developed countries, making it expensive to import due to shipping, tariffs, and currency exchange rates. Limited access to affordable financing, high interest rates, lack of collateral, and the scarcity of financial products tailored to agriculture exacerbate this challenge (Lovarelli et al., 2020).

3.2 Infrastructural limitations

The availability of precision technologies like automated feeders, wearable sensors, and software platforms for analyzing dairy production depends on the local manufacturing and distribution infrastructure. For instance, sensors for cow monitoring (health, feeding, and mil king) require reliable internet and network connectivity to function effectively (Kedari et al., 2018). Limited access to refrigeration infrastructure makes it difficult to store milk safely, leading to spoilage and reducing the economic value of increased productivity from Precision Dairy Farming practices. The isolation of many farms makes transporting milk and other dairy products challenging. This limits farmers' ability to access broader markets or processing facilities, reducing the economic incentives to adopt Precision Dairy Farming technologies that boost production (Jozsef et al., 2019; Schokker et al., 2022; Lovarelli et al., 2020).

3.3 Environmental and climatic challenges

Frequent droughts and high temperatures significantly impact cattle health and productivity in Africa, exacerbating challenges in water and feed availability. Increased frequency of droughts and heat stress leads to reduced livestock productivity, particularly in Ethiopia, where climate change poses severe risks to smallholder farmers (Degefu and Milkias, 2020). Heat stress affects cattle's gastrointestinal health, leading to decreased nutrient absorption and overall productivity (Roths et al., 2023). Water scarcity in arid regions limits the implementation of water-intensive precision systems, hindering effective heat stress management (Pavanello et al., 2024). Feed scarcity, exacerbated by overgrazing and land degradation, restricts the potential of precision nutrition tools to enhance livestock productivity (Degefu and Milkias, 2020). While Precision Dairy Farming can optimize grazing management, limited access to sufficient pasture due to land degradation remains a significant bottleneck (Degefu and Milkias, 2020; Piemontese et al., 2024).

3.4 Low digital literacy and limited training for farmers

Smallholder farmers face significant barriers to adopting Precision Digital Farming Precision Dairy Farming technologies, primarily due to a lack of awareness, digital literacy, and access to training and support (Abdul-Rahim, 2022; Mawazo et al., 2023). These challenges hinder their ability to utilize Precision Dairy Farming systems effectively, ultimately limiting the potential benefits of such technologies. Many smallholder farmers lack basic digital skills, such as internet browsing and using mobile applications, which are essential for engaging with PDF technologies (Abdulai, 2024). Training programs on Precision Dairy Farming systems are often unavailable in rural areas, leaving farmers without the necessary knowledge to operate and maintain these technologies (Abdulai, 2024; Mushi et al., 2024). Extension services, which could provide education on best practices, are limited, restricting farmers' ability to maximize the benefits of Precision Dairy Farming tools (Abdulai, 2024). Once installed, Precision Dairy Farming systems require ongoing maintenance and troubleshooting, which necessitates technical knowledge that many farmers lack (Mushi et al., 2024). The scarcity of local support for repairs and upgrades diminishes the lifespan and utility of PDF technologies (Mushi et al., 2024).

3.5 Data collection and management challenges

Data collection is information about cows, their health, milk production, and feeding record. However, in Africa, there may not be enough technology or resources to collect this data effectively. Smallholder dairy systems lack comprehensive data recording practices, which limits the ability to track animal performance and health (Ojango et al., 2022). After collecting data, it needs to be organized and stored properly. This is called data management. Farmers need to keep track of all the information they gather to make good decisions. For instance, if a farmer knows that a cow is not producing enough milk, they can change its diet or check for health issues (Kuteesa and Kyotalimye, 2019). The integration of advanced technologies is still in its infancy, with many farmers unable to utilize these tools for real-time monitoring of animal health and behavior (Liu et al., 2023; Tutkun, 2023). Challenges in implementing machine vision processes in commercial settings further complicate the adoption of precision dairy farming technologies (Liu et al., 2023). A lack of trained personnel in data management and analysis limits the effectiveness of existing systems.

3.6 Policy and market constraints

Precision dairy farming in Africa faces several policy and market constraints that hinder its adoption. The cost of precision dairy farming technologies can be prohibitive for smallholder farmers, limiting their access to advanced tools (Tutkun, 2023; Domaćinović et al., 2023). Insufficient access to credit and financial services restricts farmers from investing in necessary technologies (Tagba et al., 2024).Collaborative quality control strategies between farmers and processors can enhance supply chain management, but require government intervention and support (Yang et al., 2023). Many technologies are developed without considering the specific needs of African farmers, resulting in low adoption rates (Bewlwey, 2010). Inadequate legal frameworks for technology adoption and animal health standards hinder the implementation of precision farming practices (Omore and Waithaka, 2011). The lack of collaboration between public and private sectors limits the development and dissemination of innovative solutions (Omore and Waithaka, 2011).

3.7 Lack of adapted PDF technologies for African condition

Many Precision Dairy Farming tools are designed for high-yielding breeds in Europe or North America, which may not be directly applicable to African indigenous breeds. The adaptation of Precision Dairy Farming tools for African indigenous cattle presents significant challenges due to the unique environmental conditions and genetic characteristics of these breeds (Kim et al., 2017). Key genes associated with heat tolerance and resilience to diseases like trypanosomiasis has been identified, highlighting the need for tools that align with these traits (Kambal et al., 2023). The lack of customization in these tools means they cannot effectively monitor or support the unique needs of indigenous breeds, which have different physiological responses compared to commercial breeds (Matete et al., 2010). There is an opportunity to develop tailored Precision Dairy Farming technologies that incorporate the genomic insights of indigenous breeds, enhancing their functionality in local conditions (Tijjani et al., 2024). Innovations in electronic identification and monitoring systems could be adapted to better suit the environmental challenges faced by African cattle (Matete et al., 2010).

4 Opportunities for precision dairy farming in Africa

Precision dairy farming presents significant opportunities for enhancing dairy production in Africa, leveraging advanced technologies to improve animal health, productivity, and sustainability.

4.1 Improve animal health

Wearable sensors are revolutionizing livestock management by enabling early disease detection and optimizing animal care. These technologies allow farmers to monitor health indicators in real-time, leading to timely interventions that can significantly reduce mortality rates and enhance productivity (Vigneswari and Vijaya, 2022). Advanced feeding systems monitor individual feed intake, ensuring optimal nutrition tailored to each animal's needs, which leads to healthier livestock and increased milk yields (Arora, 2024; Vlaicu et al., 2024). Automation in feeding reduces labor costs and improves efficiency, contributing to better overall farm management (Vlaicu et al., 2024). Effective heat stress management not only improves animal welfare but also enhances productivity by maintaining optimal health conditions (Džermeikaitė et al., 2023).

4.2 Empowering smallholder farmers with digital and mobile solutions

The integration of mobile apps and digital mobile solutions facilitates the sharing of best practices, ultimately leading to enhanced productivity and reduced risks (Singh et al., 2023). Mobile phones and apps significantly improve access to market pricing and production methods, crucial for informed decision-making (Nwangwu et al., 2024). Real-time data on herd health and productivity allows farmers to optimize their operations (Abiri et al., 2023). Digital tools enable the collection and analysis of data, supporting better management of resources and inputs (Abiri et al., 2023). The use of mobile agricultural advisories has been shown to enhance the adoption of best practices, leading to improved yields (Adla et al., 2024). By bridging the information gap, these technologies promote equitable access to agricultural knowledge, fostering economic empowerment (Singh et al., 2024).

4.3 Supporting economic growth and rural livelihoods

The integration of Precision Dairy Farming technologies can significantly enhance economic growth and rural livelihoods, particularly for women in dairy farming. Enhanced milk quality can open new markets and increase profitability (Ezeanya-Esiobu et al., 2019). Precision Dairy Farming tools empower women with critical data and knowledge, improving their decision-making capabilities (Ratnasari and Sugiyanto, 2023). Women can form cooperatives to share resources and negotiate better prices, enhancing their economic standing (Desai, 2024; Malhotra et al., 2024). Increased incomes allow for better investment in education and health services within rural communities (Kamala and Jyothi, 2018). Precision Dairy Farming technologies promote sustainable farming practices, contributing to long-term community resilience (Ratnasari and Sugiyanto, 2023).

4.4 Growing demand for dairy products

The increasing urban population in Africa is significantly driving the demand for dairy products, necessitating enhanced local production to reduce reliance on imports. By implementing productivity-enhancing strategies, local farmers can meet this demand, thereby supporting food security and nutrition, particularly in rural areas (Ngeno, 2024). Implementing sustainable practices such as cut-and-carry feeding systems and agro-forestry can enhance productivity while maintaining environmental integrity (Chagunda et al., 2016). Training farmers in modern husbandry practices and management can lead to better productivity outcomes (Chagunda et al., 2016). Increased dairy production directly contributes to food security by providing essential protein sources in rural diets (Michalk et al., 2019).

4.5 Driving sustainability and environmental protection

Driving sustainability in dairy production involves optimizing feed and managing animal health to reduce enteric methane emissions. Precision Dairy Farming tools, such as GPS-enabled grazing management systems, play a crucial role in preventing overgrazing and maintaining soil quality. Incorporating additives like 3-nitrooxypropanol and macroalgae can significantly lower methane production, with reductions of up to 98% observed (Kelly and Kebreab, 2023). Identifying low methane-emitting animals through genetic profiling can enhance overall herd efficiency (Frederick et al., 2024; French, 2023). Early nutritional strategies can influence lifetime emissions, emphasizing the importance of calf health in sustainability efforts (French, 2023). Implementing effective manure management techniques can reduce pollution and facilitate biogas production, contributing to renewable energy sources (Burton and Turner, 2003; Szogi et al., 2015; Galati et al., 2023).

4.6 Public-private partnerships and investment

Public-Private Partnerships present significant opportunities for enhancing the adoption of affordable solutions in African dairy farming. By leveraging the strengths of both public and private sectors, these partnerships can facilitate access to innovative technologies and training, ultimately promoting sustainable agricultural practices. Governments can provide financial incentives and training programs to help farmers adopt new technologies, making them more accessible. Investment in rural infrastructure, such as roads and storage facilities, can enhance market access for dairy farmers (Tireuov et al., 2023). Partnerships with NGOs can facilitate the distribution of technology and training resources to smallholder farmers, ensuring they are equipped to utilize new tools effectively (Mangeni, 2019). International organizations can support capacity-building initiatives that enhance farmers' skills in using digital tools and sustainable practices (Agarwal, 2023). Implementing digital literacy programs can empower farmers to leverage technology, improving productivity and market engagement (Dowd-Uribe, 2023). Encouraging a culture of technology adoption in rural areas can lead to long-term sustainability in agricultural practices (Khaspuria et al., 2024).

4.7 Strengthening dairy market and supply chain resilience

The integration of digital platforms and cold storage solutions in the dairy market significantly enhances supply chain resilience and reduces milk spoilage. By leveraging technology, farmers can connect directly with buyers, ensuring fair pricing and improved market access. This digital transformation not only optimizes production management but also enhances traceability, which is crucial for meeting consumer demands, especially in export markets (Basu and Galiè, 2021).

Digital platforms facilitate direct connections between farmers and consumers, minimizing reliance on middlemen. This approach allows farmers to negotiate better prices, increasing their profit margins and market competitiveness (Liyanage et al., 2022). Improved cold storage facilities reduce spoilage rates, ensuring a higher volume of milk reaches markets. Digital tools enable better tracking of milk quality and production practices, addressing consumer concerns about food safety and sustainability (Emmanouilidis and Bakalis, 2020). Enhanced traceability is increasingly demanded by consumers, particularly for export products, ensuring compliance with international standards (Issar et al., 2003).

5 PDF technology and their applicability in Africa

5.1 Wearable sensors for health and activity monitoring

Wearable sensors are transforming health and activity monitoring in livestock, particularly in cattle. Continuous monitoring of behaviors such as grazing and resting provides insights into animal welfare (Miller et al., 2024). Machine learning algorithms enhance the accuracy of health assessments and behavior classification (Shi et al., 2023).

5.2 Automated milking systems

Automated Milking Systems offer significant advantages in dairy farming, particularly in enhancing milking efficiency and maintaining milk hygiene. These systems allow cows to be milked with minimal human intervention, leading to increased productivity and better data management for farmers. Automated Milking Systems can increase milk yield by up to 15% compared to traditional milking methods (Vladimirov et al., 2024). The integration of feeding stations with Automated Milking Systems has shown to enhance milking efficiency, increasing daily milk yield significantly (Piwczyński et al., 2023). AMS can maintain milk quality comparable to conventional systems, with similar somatic cell counts (Comper et al., 2023). Robotic systems also improve udder hygiene, reducing bacterial contamination significantly (Vladimirov et al., 2024). Community-based Automated Milking Systems services can lower costs for smallholder farmers, making technology more accessible (Kimmerer and Artelle, 2024). Shared use of Automated Milking Systems can optimize resources and improve overall productivity in smaller farming operations. Precision feeding can enhance milk yields by providing tailored diets, as demonstrated by models predicting higher production rates with optimized feeding strategies (Campos et al., 2023). Technologies like machine vision can detect feeding patterns and health issues early, contributing to better animal welfare (Jiang et al., 2024).

5.3 Automated environmental monitoring and cooling systems

Automated environmental monitoring and cooling systems are essential for maintaining optimal conditions in cow barns, particularly in hot climates. These systems integrate sensors to measure temperature, humidity, and ventilation, which can be linked to cooling mechanisms like fans and sprinklers. The implementation of solar-powered solutions further enhances their viability in regions with limited energy resources, such as many African countries. Systems utilize sensors to monitor barn climate, including temperature, humidity, and air quality, providing real-time data for effective management (Leliveld et al., 2024). Information is processed and visualized on user-friendly dashboards, allowing farmers to make informed decisions regarding cow welfare (Leliveld et al., 2024). Solar panels power cooling systems, such as foggers, which significantly reduce air temperature and improve cow comfort (Prakash et al., 2024).

5.4 Milk analyzers and somatic cell counters

Somatic Cell Count serves as a key indicator of udder health, with higher counts often correlating with mastitis infections (Halasa and Kirkeby, 2020; Neculai-Valeanu and Ariton, 2022). Studies show that Somatic Cell Counters can effectively guide selective dry cow treatment and monitor milk quality (Rowe et al., 2023). Recent advancements include smartphone-based Somatic Cell Counters testing, which offers a portable, low-cost solution for on-site monitoring, making it accessible for resource-limited settings (Sun et al., 2024). This method provides results within two minutes, significantly improving the speed of mastitis detection (Sun et al., 2024). Shared access to milk analyzers at cooperative facilities can reduce costs for smallholders, promoting better health management and milk quality across the dairy sector (Nyekanyeka, 2011; Ton et al., 2016).

5.5 Geospatial tools and GPS-enabled grazing management

Geospatial tools and GPS-enabled technologies are revolutionizing grazing management by providing precise monitoring of pasture conditions and animal movements. Satellite imagery and machine learning are increasingly used to quantify grassland biomass, essential for sustainable grazing management (Ogungbuyi et al., 2023). GIS tools facilitate the assessment of pasture productivity and botanical composition, aiding in effective grazing strategies (Angerer, 2012, Batykova et al., 2024). GPS collars have shown promise in accurately recording grazing events, with studies indicating a mean location error of 5.4 m, enhancing data reliability for pasture management (Hofmann, 2022). Integrating digital tools with stakeholder collaboration can improve adaptive management practices in rangelands (Bestelmeyer et al., 2024; Raji, 2024).

5.6 Mobile apps for farm management and data analysis

Mobile applications for farm management and data analysis are transforming agricultural practices, particularly in livestock farming. Apps enable efficient recording and analysis of farm data, enhancing decision-making capabilities("Exploring the Role of Smartphone Apps for Livestock Farmers Data Management Extension and Informed Decision Making in Nigeria", 2023) (Sennuga et al., 2023). Farmers receive timely updates on weather, market prices, and disease alerts, which are vital for operational success("Exploring the Role of Smartphone Apps for Livestock Farmers Data Management Extension and Informed Decision Making in Nigeria", 2023) (Schulz et al., 2022). Applications like BovCria assist in calculating reproductive and productive efficiency, making complex data accessible to users (Tarouco et al., 2023).These platforms foster virtual communities for knowledge sharing among farmers, enhancing collective learning("Exploring the Role of Smartphone Apps for+ Livestock Farmers Data Management Extension and Informed Decision Making in Nigeria", 2023). Table 1 to Summarize for different PDF tools in Africa.

6 Pathways to overcome PDF adoption barriers

6.1 Enhancing affordability through subsidies and financing

Governments and development organizations can play a crucial role in facilitating access to PDF technologies for smallholder farmers through various financial strategies. Governments can implement Green Technology Operation Subsidies (GOS) and Green Technology Investment Subsidies (GIS) to encourage farmers to adopt PDF technologies (John et al., 2023; Shi et al., 2024; Khaspuria et al., 2024). Direct subsidies have been shown to significantly enhance the profitability and sustainability of agricultural practices, particularly for small-scale farmers (Fan et al., 2013; Ren et al., 2019). Collaborations with microfinance institutions can provide tailored loan products, enabling gradual investment in PDF technologies (Zaidi and Shah, 2023; Rahaman et al., 2024). Fin Tech solutions can facilitate access to loans and market linkages, promoting financial inclusion and empowering smallholder farmers (Joy et al., 2024). Farmers can form cooperatives to share the costs of purchasing expensive Precision Dairy Farming equipment, such as milk analyzers and automated feeders, thereby reducing individual financial burdens (Twine et al., 2019).

TABLE 1 Summarize for different PDF tools in Africa.

Tool	Description	Purpose	Relevance to Africa	References
Automated Milking Systems	Automated machines for milking cows	Milk collection and data tracking	Limited adoption due to high costs but could improve productivity in commercial dairy farms	Mkwizu et al. (2019).
Milk Analyzers	Analyze milk components (fat, protein, SCC)	Milk quality monitoring	Improves milk quality for better market ability and reduces rejections in value-chain markets	Mukasafari et al. (2024). Ariong et al. (2024).
Mastitis Detectors	Identify early signs of mastitis	Animal health and milk yield	Helps farmers avoid losses due to mastitis	Shinga (2018).
Wearable Sensors	cows to monitor physiological and behavioral parameters	Health and activity tracking	Useful in detecting heat stress, estrus (heat), and early illness in low-tech environments	Visser et al. (2020).
GPS and RFID Tags	Track animal movement and identify individual cows	Herd management and tracking	Supports extensive grazing systems and traceability for disease control	Hofmann (2024).
Infrared Thermometers	Non-invasive temperature measurement	Detecting heat stress/fever	Helps in early detection of diseases like mastitis in areas with limited veterinary services	Bang et al. (2022).
Feed Quality Analyzers	Tools to analyze feed for nutrient content	Nutritional management	Addresses challenges in ensuring consistent feed quality due to local feed variability	Maleko et al. (2018).
Environmental Sensors	Measure temperature, humidity, and ammonia levels in barns	Optimize housing environment	Helps mitigate heat stress and ensure proper ventilation in hot climates	Visser et al. (2020)
Mobile Apps	Smartphone apps for tracking and managing herd data	Accessibility and convenience	Affordable and user-friendly for smallholder farmers with mobile phones	Bateki et al. (2021)

6.2 Developing low-cost and locally tailored technologies

Collaborating with local tech companies, research institutions, and universities to develop affordable Precision Dairy Farming technologies for African smallholders can significantly enhance agricultural productivity and sustainability. Engaging smallholders in the design process improves their ability to use technology effectively, fostering a sense of inclusion in value chains (Agyekumhene et al., 2020). Platforms designed with input from farmers can facilitate better communication regarding farm conditions and needs, enhancing their participation in agricultural partnerships (Agyekumhene et al., 2020). Developing simplified technologies, such as SMS-based monitoring systems, can provide critical data on health and market information without requiring internet access, making them accessible in low-resource settings (Nakalembe et al., 2021). Solar-powered cooling systems and basic wearable health sensors can be designed to meet the environmental and infrastructural challenges faced by smallholders (Woomer et al., 2021) development of low-cost, open-source systems can provide flexible, farmer-focused tools that reduce initial investment costs (Everett et al., 2023).

6.3 Expanding training and education for farmers

Agricultural extension programs can significantly benefit from incorporating digital tools and training, particularly in the context of promoting Precision Digital Farming methods. Digital tools facilitate non-face-to-face interactions, allowing extension workers to deliver information effectively, leading to tangible adoption outcomes (Dahlan et al., 2024). Mobile phones and other ICT tools enhance market participation by providing timely access to market information, which is crucial for informed decision-making (Nwangwu et al., 2024). Training programs that focus on digital literacy and data interpretation empower farmers to utilize mobile apps and sensors confidently (Yang et al., 2024). Enhanced digital literacy correlates with increased pro-environmental behaviors among farmers, promoting sustainable practices (Lu et al., 2024).

6.4 Improving infrastructure and connectivity

Improving infrastructure and connectivity in rural areas is crucial for enhancing farmers' access to digital tools and resources. Investments in internet and mobile network access, particularly through renewable energy solutions, can significantly bridge the digital divide. Sharing resources among mobile network operators can lead to the deployment of green energy-powered base stations, ensuring efficient connectivity in rural areas (Dlamini and Vilakati, 2021). Utilizing solar-powered mesh networks can optimize internet access while promoting environmental sustainability (Benitez, 2024). Establishing cold chain systems for milk storage can reduce spoilage and maintain quality, even in remote locations (Carter and Marshall, 2019). Targeted digital skills training can empower farmers, enhancing their ability to utilize cloud-based tools effectively (Carter and Marshall, 2019).

6.5 Encouraging public-private partnerships and investment

Encouraging public-private partnerships and investment incentives can significantly enhance the development of Precision Dairy Farming solutions tailored for smallholder farmers in Africa. PPPs facilitate the sharing of resources and risks between public institutions and private companies, enhancing innovation in agricultural technology (Mangeni, 2019). They create marketing channels that connect private sector capabilities with smallholder needs, ensuring that technologies reach those who need them most (Roy and Christy, 2005). Public private partnership can help bridge the gap between private intellectual property rights and public research, enabling the development of technologies like genetically modified crops for smallholders (Dowd-Uribe et al., 2024). NGOs can play a crucial role in funding and disseminating Precision Dairy Farming technologies, helping to overcome barriers related to knowledge and resources (Mangeni, 2019).

6.6 Promoting data-driven decision-making and local data collection

Promoting data-driven decision-making in African agriculture hinges on localized data collection and analysis tools. By gathering region-specific data on milk production, animal health, and environmental factors, predictive models can be tailored to African conditions, enhancing the relevance and accuracy of insights. Implementing geographic information systems for systematic data collection can improve agricultural interventions and decision-making processes (Mathenge et al., 2022). Establishing protocols for local data collection ensures that the data is reliable and accessible, which is crucial for effective food assessments (Carcedo et al., 2023). Initiatives like the Africa Dairy Genetic Gains program provide farmers with access to genomic data and breeding management support, enhancing productivity (Meseret et al., 2022).

6.7 Creating policy and regulatory support

Creating effective policy and regulatory support for sustainable agriculture and precision farming Precision Dairy Farming is essential for reducing costs and enhancing access to these technologies. Governments can implement various strategies, including financial incentives and cooperative structures, to facilitate the adoption of Precision Dairy Farming tools among smallholders. Offering tax reductions and grants can lower the financial burden on farmers adopting Precision Dairy Farming technologies, making it more feasible for smallholders to invest in these systems (Macrae et al., 1990). Encouraging cooperative farming through financial support can enable smallholders to share resources and access advanced technologies collectively (Sanyaolu and Sadowski, 2024). Investing in training programs and research can enhance farmers' understanding and implementation of Precision Dairy Farming technologies, leading to improved productivity and sustainability (Macrae et al., 1990).

6.8 Developing knowledge-sharing platforms and farmer networks

Establishing digital platforms and community-based farmer networks is crucial for enhancing knowledge sharing and promoting the adoption of sustainable agricultural practices. These platforms facilitate communication among farmers, enabling them to share experiences, troubleshoot issues, and access expert advice, which can significantly boost confidence in new technologies like Precision Digital Farming. Platforms designed for knowledge co-creation allow farmers to integrate local and scientific knowledge, leading to context-specific agricultural practices (Pathirage and Ginige, 2022). Farmer-to-farmer communication networks enhance trust and credibility, as early adopters share their positive experiences with Precision Dairy Farming technologies (Izuchukwu et al., 2023; Teodoro et al., 2023).

6.9 Promoting sustainable practices and environmental benefits

Promoting sustainable practices in agriculture, particularly through the integration of precision feeding Precision Dairy Farming, can significantly enhance environmental benefits and farmer resilience. Educating farmers on the advantages of Precision Dairy Farming, such as improved feed efficiency and waste management, can incentivize its adoption. Precision Dairy Farming optimizes nutrient intake, reducing waste and improving livestock health (Kamakaula, 2024). Enhanced feed management minimizes environmental pollution from manure (Abobatta and Fouad, 2024). This method improves soil health and biodiversity, complementing Precision Dairy Farming efficiency (Rajput et al., 2023). Sustainable practices reduce water usage, essential in climate-affected regions (Saikanth et al., 2023). Implementing precision feeding can allow farmers to earn income through carbon credits, promoting further adoption (Kodaparthi et al., 2024). Table 2 the Pathways to overcome Precision Dairy Farming (PDF) adoption barriers in Africa.

TABLE 2 Pathways to overcome precision dairy farming (PDF) adoption barriers in Africa.

Barrier	Pathways to Overcome	Key Stakeholders
Infrastructure Limitations	- Reliable Internet and Electricity - Mobile Connectivity - Invest in rural electrification (e.g., solar-powered systems).	Governments, NGOs, Private Sector
	Develop affordable, low-connectivity PDF tools for remote areas.	Research Institutes
	- Improve access to broadband and mobile networks in rural areas.	Telecommunication Companies
Lack Access to Technology	-Affordable Devices and Software -Developing or adapting lower-cost sensors, devices, and software specifically designed for the African	Subsidies or microfinance options could be provided to make these technologies more affordable.
	- Cost Reduction	
	-Government and NGO Support	
Limited Access to Finance	- Provide government-backed subsidies or low-interest loans for PDF adoption.	Governments, Microfinance Institutions
	- Establish cooperatives for shared technology use and cost-sharing among farmers.	Dairy Cooperatives, Farmer Groups
	- Promote partnerships	Companies, Private Lenders
Knowledge & Skills Gap	- Offer training programs on PDF technologies and practices through extension services.	Agricultural Extension Services
	Collaborate with universities and research centers to develop hands-on training modules for farmers.	Academic Institutions, NGOs
	- Use mobile apps or digital platforms to provide real-time guidance and support to farmers.	App Developers, Telecommunication Firms
Lack of Policy Support	- Advocate for policy frameworks that support PDF adoption, including tax incentives	Governments
	Establish public-private partnerships to fund large-scale PDF programs.	Governments, Private Sector

7 Case studies

7.1 The Dairy Development Program in Kenya

The Dairy Development Program in Kenya has significantly enhanced milk production and the livelihoods of smallholder dairy farmers through innovative technologies and training. The introduction of mobile applications for record-keeping and tracking has proven effective, with farmers reporting a 20-30% increase in milk production due to improved management practices. Additionally, the use of artificial insemination (AI) has led to better herd genetics, resulting in healthier animals and increased yields.

Mobile applications facilitate data collection and performance monitoring for small dairy farms, allowing farmers to track milk yield and breeding cycles effectively (Fouad et al., 2021). Farmers using these applications have reported significant increases in milk production, attributed to better feed management and breeding practices (Marwa et al., 2020). The AI program has improved herd genetics, leading to healthier animals and higher milk yields, which is crucial for smallholder farmers' income (Marwa et al., 2020). Enhanced genetics contribute to the overall productivity of dairy farms, ensuring sustainability in the sector (Smollo et al., 2017). Training programs on dairy management practices have increased farmers' knowledge and confidence, further boosting productivity (Marwa et al., 2020).

7.2 Bokomo Foods' Dairy Cooperative in South Africa

Bokomo Foods' Dairy Cooperative in South Africa has effectively utilized technology to enhance milk production and processing efficiency among smallholder farmers. By implementing GPS tracking systems, quality monitoring protocols, and mobile applications, the cooperative has significantly improved logistics, quality assurance, and market access. This technological integration has led to a reported 40% increase in milk sales, demonstrating the cooperative's positive impact on the farmers' livelihoods.

GPS Tracking Systems optimize logistics, ensuring timely collection and delivery of milk, which is crucial for maintaining quality (Mdoda et al., 2024). Rigorous testing protocols enhance milk quality, meeting both local and international standards (Fouad et al., 2021). Farmers can track production data, facilitating better management and decision-making (Gichamba and Lukandu, 2012). The cooperative model allows smallholder farmers to pool resources, improving their bargaining power (Ortmann and King, 2006). The cooperative fosters a network for knowledge transfer, enhancing production techniques and overall productivity (Mdoda et al., 2024; Svensson et al., 2023).

7.3 The East African Dairy Development Project

The East African Dairy Development Project has significantly transformed the livelihoods of smallholder dairy farmers in Kenya, Uganda, and Tanzania through innovative practices and technologies. By integrating mobile technology for data collection, artificial insemination, and nutritional assessments, the project has empowered over 250,000 farmers, leading to a remarkable 50% increase in average milk yields and enhanced household incomes.

Mobile applications facilitate real-time data collection and management, allowing farmers to monitor performance and make informed decisions (Fouad et al., 2021). The Cow service in Kenya exemplifies the impact of ICT, increasing annual milk production per cow by 13% and household income by 22% (Marwa et al., 2020). The use of artificial insemination has been promoted to improve breeding practices, enhancing milk productivity ("Machine learning models for predicting decisions to be made by small scale dairy farmers in Eastern Africa", 2023). Nutritional assessments guide farmers in adopting better feeding practices, which are crucial for maximizing milk yields (Singh et al., 2023). Dairy hubs serve as critical linkages between smallholder farmers and large processors, improving access to markets and essential services (Omondi et al., 2017). These hubs enable collective marketing, which enhances farmers' bargaining power and income stability (Omondi et al., 2017).

7.4 The Heifer International Program in Ethiopia

The Heifer International Program in Ethiopia has significantly enhanced dairy production and food security through the introduction of high-quality breeds and improved management practices. The program's multifaceted approach, including training in nutrition management, artificial insemination, and record-keeping, has empowered farmers, particularly women, leading to a reported 60% increase in milk production and improved family nutrition.

Enhanced training programs have been shown to increase milk production by up to 26.6% when combined with improved feed and management practices (Hatew et al., 2023). Training on dairy husbandry resulted in a 21.7% increase in milk production and a 22.5% rise in milk income (Seble et al., 2020). Adoption of improved dairy farming practices led to a 31% increase in household food consumption and a 26% improvement in dietary diversity (Feyisa et al., 2023). The program's focus on women's empowerment has enhanced their roles in dairy management, contributing to better household income and nutrition (Hatew et al., 2023).

8 Roadmap for sustainable dairy production in Africa

In precision dairy farming, sustainability refers to the ability to optimize dairy production while minimizing environmental impact, ensuring economic viability, and promoting animal welfare (Biswas et al., 2024). It involves using advanced technologies such as sensors, automated milking systems and data analytics to improve resource efficiency, reduce waste, and enhance milk yield without depleting natural resources or harming animal health (Milan et al., 2018). A strategic roadmap for sustainable dairy production in Africa is essential to address the evolving challenges and opportunities within the sector.

Collaboration between governments, NGOs, and the private sector can facilitate funding and development of affordable PDF technologies tailored for smallholders (Liu et al., 2023; Kaur et al., 2023). Investment in IoT, AI, and computer vision can enhance monitoring of animal health and behavior, leading to better management practices (Liu et al., 2023). Implementing cost-effective solutions can help smallholder farmers adopt these technologies without significant financial burden (Kaur et al., 2023). Mobile apps can provide farmers with real-time data on animal health, feeding, and market trends, enhancing decision-making (Tutkun, 2023). Digital platforms can connect farmers with experts for guidance on best practices, improving productivity and animal welfare (Kaur et al., 2023).

Training programs should focus on practical skills, such as antimicrobial stewardship in dairy cattle, which enhances disease management and treatment success (Garzon et al., 2023). Incorporating local knowledge systems into training can enhance relevance and effectiveness, ensuring that programs are culturally appropriate and context-specific. Cooperatives allow smallholder farmers to combine resources, which can lead to better bargaining power in markets (Li et al., 2024). Membership in cooperatives improves farmers' access to credit by reducing transaction costs and providing financial institutions with better information about farmers (Jiang et al., 2024). Providing training enhances the management skills of cooperative leaders, which is crucial for operational success (Bhattarai and Pandit, 2023).

Financial institutions can create specific credit mechanisms that cater to the unique cash flow needs of farmers, allowing them to invest in sustainable technologies. Efficient transport methods, such as vehicles or tractors, enable timely and quality delivery of milk, increasing market participation among smallholder dairy farmers (Musitini and Muroiwa, 2019). Infrastructure can decrease losses, which are particularly high in developing regions, thereby increasing overall supply chain efficiency (Usman and Haile, 2022). Government initiatives that address market access factors can significantly boost commercialization levels among smallholder dairy farmers (Ageya and Omondi, 2016). Facilitating branding and certification helps smallholders meet quality standards, making their products more competitive (Tyagi et al., 2019). Utilizing a range of policy instruments such as subsidies, training, and market access can significantly enhance the adoption of climate-smart agricultural practices among smallholders (Asseldonk et al., 2023). Policies should consider indirect effects and promote integrated strategies that enhance the adoption of sustainable practices (Asseldonk et al., 2023).

9 Conclusion

Precision Dairy Farming represents a transformative approach to dairy farm management, leveraging advanced technologies and data analytics to enhance the monitoring and welfare of individual animals. This innovative framework facilitates informed decision-making by systematically collecting and analyzing critical data on milk yield, composition, and animal health behavior. The integration of technologies such as pedometers, automatic temperature recorders, and estrus detection monitors, Wearable Sensors, Automated Milking system, Mobile Apps and Geospatial Tools are vital in addressing the unique challenges faced by the dairy sector in Africa. Based on various empirical studies, the implementation of this technological advancement has resulted in a 30% augmentation in milk production, a 25% diminishment in feed expenditures, and a 20% decline in veterinary costs. Furthermore, it is imperative to advance the monitoring of animal health, refine decision-making processes, alleviate labor demands, and bolster financial stability. It is constrained by numerous barriers, including high technology costs, inadequate infrastructure, limited access to training and financial resources, Environmental and climatic constraint, low digital literacy and Policy and Market Constraints. To overcome these challenges, targeted initiatives that foster collaboration among governments, NGOs, and the private sector are crucial. Such partnerships can create supportive environments that encourage investment in technology and training programs, ultimately enhancing the capacity of farmers to effectively implement these advancements. Thus, the future of dairy farming in Africa hinges on the successful integration of precision technologies, which can lead to a more resilient and productive industry, ultimately benefiting farmers and communities.

Author contributions

ET: Conceptualization, Investigation, Resources, Validation, Writing – original draft, Writing – review & editing, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Software, Supervision, Visualization. DW: Conceptualization, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. DY: Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. TM: Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AM: Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing, Validation.

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