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Smart Practices in Modern Dairy Farming in Bangladesh: Integrating Technological Transformations for Sustainable Responsibility

Mohammad Shamsuddoha [1,*] and Tasnuba Nasir [2]

[1] Department of Management and Marketing, Western Illinois University, Macomb, IL 61455, USA
[2] School of Business, Quincy University, Quincy, IL 62301, USA; t.nasir59@quincy.edu
* Correspondence: m-shamsuddoha@wiu.edu

Abstract: The current Bangladeshi dairy sector faces many problems related to sustainability indicators from economic, social, and environmental perspectives. In this circumstance, they must combine cutting-edge innovation to overcome growing sustainability concerns and technical revolutions to become smart farms. This study analyzes how dairy farmers might use cutting-edge technologies in their dairy sub-processes to determine the benefits of achieving additional productivity and efficiency. This paper examines precision livestock farming, information analytics, and alternative energy sources to reduce environmental hazards and increase resource efficiency. Using cutting-edge technologies like artificial intelligence (AI), machine learning (ML), robotics (RPA), Internet of Things (IoT), data analytics, system dynamics, and simulation modeling can assist the farmers in improving the results. Analyzing developing country case studies and best practices reveals crucial answers for reconciling sustainability stewardship and operational efficiency. The system dynamics method builds a simulation model and finds the projected results before implementing it in real life. The findings provide considerable waste reduction and productivity gains through technological deployments. The simulation model creates two scenarios of 'current' and 'technology-adopted' processes to examine the transformational benefits of sustainable practices. A case study method was adopted for this technology deployment to organize a comprehensive strategy that blends technology and sustainability. This study ends with recommendations for dairy farmers and policymakers to create a resilient and environmentally friendly dairy operation to secure the dairy sector's long-term viability in transforming technologies. Future farms can follow the practical, technical, and policy, as well as recommendations to improve their processes, such as smart farm concepts available in academia and dairy-developed countries.

Keywords: dairy; sustainability; technology; transformation; Bangladesh

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1. Introduction

The global dairy sector faces numerous challenges in improving productivity and efficiency by adopting eco-friendly practices since consumer demand for dairy products is growing. In several developed nations, dairy farming has experienced a transformation due to innovations in technology like robotics, the Internet of Things (IoT), and artificial intelligence (AI). These advancements have raised productivity, reduced waste, and rendered precision cattle management feasible. Countries like the Netherlands and New Zealand have successfully deployed these technologies to optimize dairy operational effectiveness while addressing sustainability challenges like cow dung recycling, wastewater usage, and greenhouse gas emissions. There is no evidence of any farm having invested in all available technologies for management of the entire dairy process. There are many challenges, but farmers need to address them on a priority basis so that they can examine each transformational benefit and move forward to another advancement for more paybacks. However, the absence of financial constraints for facilities and the ignorance of dairy farmers remain obstacles to implementing these innovations in emerging economies like Bangladesh. Dairy farming in Bangladesh offers an opportunity to explore how modern technologies can address challenges, improve triple-bottom-line sustainability, and contribute to the economy. The present research aims to fill this gap by providing a spotlight on the potential of integrating cutting-edge technologies into dairy operations, thereby contributing to dialogues on environmentally friendly farming on a global basis.

Modern dairy operations incorporate innovative equipment to improve productivity and sustainability (Feil et al., 2020; Saqib et al., 2023; Saqib & Qin, 2024). For example, ML (like Allflex's SenseHub) predicts problems like mastitis, and AI (like Connecterra's Ida) improves feeding time slots and standard measurements for each cow type. RPA (like Lely Astronaut) optimizes milking, reducing costs related to labor, and IoT (like Smart Barn) maintains surveillance on stable surroundings to ensure cows feel at ease. Although system dynamics and simulation modeling applications project dairy operational outcomes and evaluate alternatives for improved decision-making, data analytics (such as DeLaval VMS) ensures real-time quality of milk monitoring, establishing the dairy industry as more environmentally friendly and efficient. There is a lack of studies in the regional context of the dairy industry, where technological solutions are scarce for common sub-processes (cattle rearing, milking, waste management, and value addition).

As a significant part of the Bangladeshi agricultural economy, the dairy industry supports the livelihoods of millions of people (Uddin et al., 2017). It offers the country's population the necessary nutritious goods. Nearly seventy percent of the rural population works in livestock and dairy production; hence, this industry is vital for maintaining rural development and food security (Shamsuddoha, 2005). However, the conventional methods used in the sector are sometimes marked by waste of resources and operational inefficiency, which drives environmental and financial tension. Moreover, the worldwide market for dairy products keeps growing, which gives dairy producers future business prospects and supplementary complications.

The dairy industry has become increasingly dependent on contemporary and effective production techniques as sustainability and technical innovation take the front stage worldwide (Henchion et al., 2022). Dairy producers must now include sustainable methods in their operations to remain competitive and handle the problems caused by resource depletion and climate change (Saqib & Zhang, 2021; Feil et al., 2020). Sustainable dairy farms not only provide a necessity but also enhance natural resource usage, cut greenhouse gas emissions, and apply animal welfare standards to boost productivity and reduce environmental impact. AI, IoT, data analytics, and renewable energy technologies can change dairy operations (Kazancoglu et al., 2022).

Third-world countries like Bangladesh still use outdated technologies, which is a prime cause of low productivity (Samad, 2020). They have failed to build robust operations and supply networks for dairy production and distribution to customers and retailers. Such failure to adopt cutting-edge technologies in dairy operations causes additional harm to the surrounding farm environment and profitability. In these circumstances, farms need to convert themselves into more sustainable and technologically integrated networks to tackle these critical concerns, ensure optimizations for adequate profit, and achieve long-term sustainability. Thus, this study examines how cutting-edge technologies and robust dairy practices might improve dairy efficiency, waste reduction, and the triple bottom line of sustainability (Feil et al., 2020).

The dairy industry in Bangladesh is encountering environmental, economic, and social challenges that obstruct its development and sustainability (Nasir, 2016). Small-scale dairy industries frequently encounter challenges when adopting modern technologies due to inadequate profits (Shamsuddoha et al., 2023b). Inadequate profit pushes the farmers to accept the losses, leading to delinquents in their businesses at some stage. In this circumstance, government subsidies, micro-finances from NGOs, private financiers, and technology vendors can provide finances that can help the farm adopt technologies. This is a common scenario for many farmers giving up dairy businesses due to inconsistent and reduced milk prices and elevated production costs. The economic condition is aggravated due to social barriers like limited access to scientific dairy process-related education and training.

Moreover, many small farmers do not know about sustainability issues related to economic, social, and environmental gains (Zainab et al., 2016). Environmental issues like insufficient waste management, water contamination, and greenhouse gas emissions deepen these difficulties. For example, dairy farms in Bangladesh are inefficient in recycling their farm wastes, which causes environmental damage and loss of potential resources for making by-products. According to case farm data, they only utilize 15–20% of their wastes (cow dung and slurries) and do not recycle their wastewater, harming the nearest sewerage systems and crop fields. The cumulative impact of these challenges hinders the dairy sector's ability to succeed in a competitive and resource-limited global market. Bangladesh is one of the most vulnerable countries, and floods, cyclones, and droughts have often impacted it. Such adverse catastrophes cause more problems for the dairy industry. Recently, Bangladesh faced a severe flood (August 2024), and many districts were under 10 feet of water. Dairy farms in those places were completely damaged, the cattle died, and farmers had to accept unimaginable losses. Due to financial incapabilities, their lack of access to advanced technologies to monitor (alarm systems based on weather forecasting) and manage resources effectively (move the feed and other resources to a dry place) resulted in wastage and inefficiencies in operations. For example, technologies related to shed management, shed height projecting possible flood water levels, and the assurance of dry feedstocks for the cattle and freshwater reservoirs could help them avoid such catastrophes. For example, the Netherlands' dairy farms utilize advanced animal shed designs and robotics to improve cow comfort, health, milk productivity, animal mortality, and operational efficiency (Gheorghe-Irimia et al., 2023). Modern technologies like AI, ML, IoT, and solar or biogas (renewable energy) sources can significantly help farms increase resource efficiency and productivity.

Table 1 shows the species available in the 2013–14 and 2022–2023 fiscal years, which reflects the progress made over the last 10 years. It is evident from Table 1 that the various species did not reproduce enough to meet the demands of the growing population in Bangladesh. Also, it demonstrates the demand and consumption rate per year. Livestock contributes to GDP by 1.85%, and livestock share the contribution of 16.52% in agriculture (DLS, 2023). Per capita, milk consumption is 221.89 (mL/day/head), which looks moderate. Unfortunately, many people with low income and middle-class people do not have the buying power to meet these demands. Most of the milk is used for further processing for value-added products, which is a deceptive presentation of actual consumption by the whole population. Bangladesh dairy needs to produce more milk to fill the gap and make it accessible and affordable to low-income people. It is noted that 18.7% of people are living under the poverty line, and 22% are living in the lower middle class.

Table 1. Dairy economy at a glance (DLS, 2023).

Name of the Species	2013–2014 (Million)	2022–2023 (Million)	Products	2013–2014 (Million)	2022–2023 (Million)
Cattle	23.49	24.86	Milk	6.09	14.07
Buffalo	1.46	1.52	Meat	4.52	8.71
Sheep	3.21	3.83		Demand	Availability
Goat	25.44	26.95	Milk	15.85	221.89 (mL/day/head)
Total Ruminant	53.59	57.14	Meat	7.61	137.38 (gm/day/head)

There is a significant gap in scientific studies on the effects of these technologies on sustainability in developing countries like Bangladesh. Thus, this paper examines the different roles of cutting-edge technologies in enhancing dairy production, sustainability, and resource utilization. This study also discovers the potential of advanced technologies and applications that can help automated milking systems using milking parlors, farm management using AI, and ML production process, as well as find a solution to use more renewable energy systems. This study also conducts an in-depth literature review on technologies used by developed dairy nations like the USA, the Netherlands, Germany, Australia, and New Zealand. For instance, the Netherlands implemented AI for demand forecasting and automated milking systems (Jensen et al., 2018), while Germany emphasizes robotic milking systems, automated feeding management, and renewable energy integration (Piwczyński et al., 2020). For example, milk demand varies due to seasonal effects, food consumption behavior, and alternatives. In this case, AI can help predict future demand to prepare milk before its utilization for value-added products. Similarly, an automated milking parlor can help the farm extract more milk yield and protect from contamination and diseases like mastitis.

For instance, New Zealand applied pasture-based dairy systems enhanced by AI and IoT technologies (Tzanidakis et al., 2023), while the Netherlands utilizes biogas systems and smart irrigation technologies to promote eco-friendly dairy farming (Beldman et al., 2021). This study considers technologies in a relatively high-yield country like India due to the numerous cattle numbers. The sections below discuss various technological advances and intend to discover the technologies that can be implemented in a country like Bangladesh. Such an accumulation of information will offer real-life implications for farmers, stakeholders, and policymakers. This will contribute to a more resilient and sustainable dairy business, which helps farmers in the face of changing worldwide problems.

The operational efficiency of dairy is the main focus of this investigation. Small and medium-sized dairy farms are the backbone of the Bangladeshi dairy industry. This study examines current dairy farming practices, sustainability issues, and innovative ways to address them. To fully understand the problem, this study employs case studies, computer simulation modeling, and scenario analysis to understand the possible impacts of transformation. Dairy farmers, policymakers, and businesspeople want to know the transformational benefits. According to this study, new tools help farmers use resources and produce more money. Research found that regulations and mechanisms that promote sustainable practices are essential. This study also demonstrates that dairy workers must integrate sustainability in business planning to preserve the sector's long-term survival. This research aims to assist the Bangladeshi dairy sector in thriving sustainably and boosting the rural economy. Here are the objectives of this study:

1. Examine how advanced technologies can enhance sustainability and efficiency in Bangladeshi dairy farm operations.
2. Assess the triple bottom line of adopting these technologies based on their environmental, social, and economic impacts, focusing on resource optimization, environmental restoration, and profitability.
3. Develop a strategic framework for integrating cutting-edge technologies into dairy operations, and provide actionable recommendations for adopting technology to farmers and policymakers.

2. Theoretical Framework

2.1. Overview of Dairy Farming in Bangladesh

The Bangladeshi agricultural economy relies on dairy farming, which supports millions of rural households (Shamsuddoha, 2009). The dairy business offers a steady income for smallholder farmers and helps meet nutritional demands, notably protein deficits, in a primarily agricultural nation. The Bangladeshi livestock sector provides 1.85% of the GDP, with dairy farming being a significant contributor (BBS, 2023). Over 1.4 million households maintain an average of 1–3 animals (Hemme et al., 2008), whereas 70% produce 70–80% of the country's milk (Datta et al., 2019). Bangladeshi dairy producers have less than five cows. Only around 10% maintain commercial dairy farm sizes. Only 2% of farmers have more than 100 cattle, and the largest dairy (Nahar Dairy) is located in Chittagong, which has more than 1700 cattle of different ages. Due to limited resources, knowledge, and infrastructure, smallholder farmers struggle to embrace modern farming methods. Low milk productivity results from traditional farming methods. Bangladeshi cows produce 0.50–2.50 L daily, far less than worldwide norms (Samad, 2020). Bad cow nutrition, inadequate veterinary care, and low-yield indigenous breeds are the leading causes of low production. Population growth, urbanization, and consumer knowledge of milk's nutritional advantages have increased dairy product demand (Gerosa & Skoet, 2012). Due to production inefficiencies and outdated infrastructure, the domestic dairy struggles to meet increased demand. With over 50% of its milk and dairy products imported, Bangladesh relies on imports (Hossain et al., 2022). Imports hurt the country's balance of payments and threaten the dairy industry's future. Smallholders lose money after harvest because of poor cold storage, transportation, and market access (Gazi, 2020). Insufficient regulatory procedures allow milk adulteration, impacting food safety and customer trust in local dairy products (Rahman et al., 2014). Environmental sustainability is another industry concern. For instance, manure management, gas emissions, and water overuse/contamination create environmental degradation (Bhusal & Thakur, 2022). Overuse of chemical pesticides and fertilizers in crop production harms soil and biodiversity.

Bangladesh Dairy Supply Network

There are multiple levels to the dairy supply chain in Bangladesh, beginning with small-scale farmers who deploy semi-modern and conventional methods for producing milk. Milk is transported to milk collection facilities that are often run by independent businesses or cooperatives. Here, quality control checks and preliminary preservation take place. Processors subsequently utilize the milk for pasteurization, which involves packaging and expanding product lines (e.g., cheese, butter). Wholesalers acquire transformed milk-related products, monitor transportation, and ensure delivery to retailers. In the end, community markets, grocery stores, or chain stores determine where the products are delivered to the end customers. Lack of infrastructure, cold storage, and efficiency affects sustainability achievements and production quality.

The Bangladesh dairy supply network is represented in Figure 1, starting with small-scale and large commercial farms producing milk. Most milk travels to milk collection centers and cooperatives to be distributed to the end customers. In this stage, milk processing companies collect milk from cooperatives or milk collection centers to process the milk for value-added products like pasteurized milk, flavored milk, cheese, butter, and many other sweet items for selling to sweet shops. The connected arrows demonstrate how dairy products and milk travel through various stages, ensuring distribution chain efficiency and quality. It is noted that milking parlors (farm level), collection centers (collection level), the production process (value-addition level), and supply networks are yet to adopt advanced technologies to obtain the maximum benefits of efficiency and sustainability.

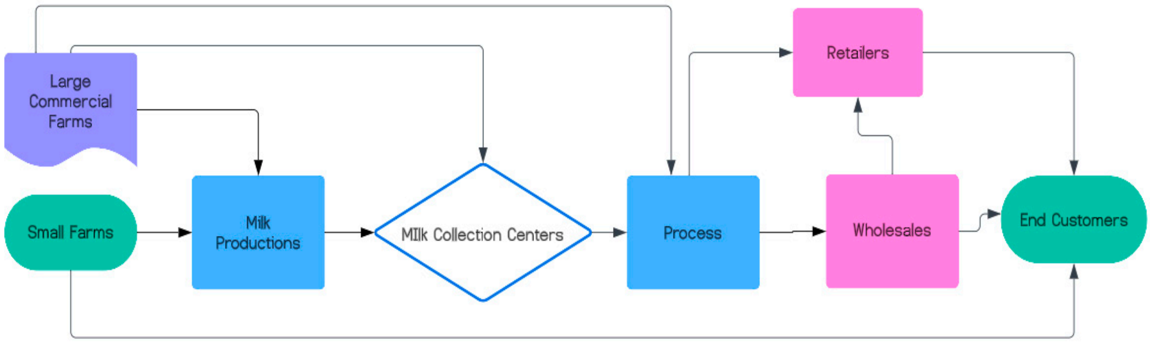

Figure 1. Bangladeshi dairy network.

2.2. Sustainable Practices

Sustainability is a rigorous theory (Harrington, 2016) implemented in many diverse industries to protect their economy, social aspects, and surrounding environments (Shamsuddoha et al., 2024). This triple-bottom-line theory includes balancing economic, social, and environmental aspects to accomplish long-term sustainable value (Adams et al., 2013). Dairy farms are no exception to other business processes as they need such theoretical implementation to address economic, social, and environmental challenges.

2.2.1. Supply Chains for the Dairy Economy

A healthy dairy economy depends on production efficiency, minimizing costs, and providing dairy farmers with a fair market price for their meat and milk products (Garcia et al., 2019). The farm accurately deploys technology to achieve substantial benefits, which is crucial to achieving economic sustainability. Efficient feeding management and automated milking machines maximize feed consumption and milk output, and help reduce expenses and waste (Bhoj et al., 2022). Lely's automated milking systems increase milk yield and reduce labor expenses (Simões Filho et al., 2020). Making it easy for small farmers to reach markets is crucial to economic survival; digital marketplaces like AgriMarketplace link buyers and vendors for better accessibility. This can help farmers negotiate better terms and reduce mediators. Blockchain can also explain the supply chain for dairy producers, assisting customers to trust locally sourced dairy products and ensuring fair remuneration (Shingh et al., 2020).

2.2.2. Making Sure the Dairy Industry Is Socially Sustainable

Social sustainability aims to improve dairy farmers' and workers' health and happiness while encouraging honest behavior throughout the supply chain. It is imperative to deal with labor safety because worthless working conditions can significantly affect farm workers' output and quality of life. Implementing IoT-based barn tracking and smart temperature control systems enhances workplace safety and comfort, improving health and productivity (Lashari et al., 2023). Another aspect of social resilience that requires improvement in the dairy sector is the inclusion of women. Access to training programs and microcredit via mobile financial applications can enhance women's participation in dairy farming (Bin Duwa bin Khoja, 2021). Such practices enhance gender equality and increase the involvement of all genders, leading to increased household incomes.

2.2.3. Utilizing Existing Resources and Protecting the Environment

A dairy farm needs common resources like water access, transportation mobility, financial sufficiency, and many more things to operate their business like other industries. Dairy farms impact the environment by not considering water wastes, water contamination, greenhouse gases through manure, and the destruction of soil using chemicals (cleaning products). For instance, Internet of Things (IoT) devices can track water and nutrients to prevent misuse and contamination. For example, IoT-enabled systems like AquaSpy assist farmers in using water efficiently, which is beneficial for the environment and keeps pastures productive (Kumar et al., 2022). Technology can also help with manure management. Biogas digesters convert waste into clean energy, reducing greenhouse gas emissions and providing an alternative energy source for agriculture (Czekała, 2022). In addition to helping with garbage removal, this also supports a circular economy in the dairy industry. Virtual fencing technology also helps control grazing patterns in a more environmentally friendly way, which stops animals from overgrazing and protects the land (Horn & Isselstein, 2022). By adding these tools to the operation, dairy farming will be more resilient and better for the Earth.

2.2.4. Integrating Technology in Various Processes

For the dairy supply line to be sustainable, they must gradually incorporate new technologies. For instance, IoT-based cattle tracking systems and data analytics platforms can help keep an eye on animals' health, make breeding programs more effective, and boost milk production, all of which contribute to a dairy farm that works well and is reliable (Hassan et al., 2023). However, getting many people in Bangladesh to use these tools will take a lot of money and help from both the public and private sectors. Educating programs, outreach services, and cooperative models can help build farmers' skills and give them the confidence to use these methods. The dairy industry will be more stable and lucrative. Modern dairy farms also integrate robust practices, which helps them maintain sustainability components. To do so, farms need to communicate with stakeholders to find appropriate technology linkages to make their relationship solid and viable in terms of sustainability.

2.3. Modern Technologies in Dairy Farming

Modern dairy farming is incrementally deploying cutting-edge innovations to deal with sustainability challenges affecting the environment, social welfare, and profitability. The technologies are available worldwide, and farmers can customize them based on their requirements. This study delivers the technological benefits to the relevant stakeholders so they can consider their incorporation based on their scope, budget, and available resources.

2.3.1. Systems for Precise Feeding

In the dairy industry, optimizing animal nutrition to boost milk and meat output while minimizing costs is an enormous challenge. Modern feeding solutions ensure that each animal obtains sufficient nutrients at the right time by tailoring feed combinations using sensors and data analytics. Technological advancements like Lely Vector and Tracker optimize and track feed intake and increase milk production (Mottram & den Uijl, 2022).

These techniques improve digestion, thus decreasing feed waste and reducing the release of methane. Such practices help to render farming more sustainable.

2.3.2. Devices Designed for Milking Cows

The GEA DairyRobot R9500 and Lely Astronaut represent significant advancements in automated milking systems (AMSs), transforming the dairy industry by enabling cows to be milked according to their schedules (Bicak et al., 2022). AMS utilizes devices to monitor the cow's health and milk nutrients, identify parasites, and identify individual milk production of each cow, thereby linking them with real-time data (Kaswan et al., 2024). This method enhances milk yield, benefits animal welfare, and minimizes operational expenses using empirical data.

2.3.3. Livestock Monitoring with IoT

IoT sensors have become a vital component of dairy production and are beneficial for environmental sustainability. Farmers can efficiently manage the herd using technologies like CowManager and Allflex Livestock Monitoring, which give them ongoing information about the health and behavior of their animals (Kaswan et al., 2024). These sensors allow for immediate action when they detect signs of disease indications, changes in dietary habits, or ovulation cycles. This preventative health care makes animals happier and healthier, cuts down on vet bills, and boosts milk production, making dairy farming more sustainable economically and socially.

2.3.4. Waste Management with Biogas Digesters

Taking care of manure is a significant environmental problem for dairy farms. Biogas digesters are an excellent option because they turn waste into renewable energy. This reduces greenhouse gas emissions and gives farms another energy source (Saha et al., 2024). Biogas can be used for warmth, for energy, or even to power farm equipment, which makes the dairy farm a circular economy. Technologies like PlanET Biogastechnik make this process easier, which helps farms sustainably deal with trash while making extra money.

2.3.5. Blockchain for Openness in Dairy Farms

Adding blockchain technology to dairy processes makes them more open and accessible to track, which protects product quality and encourages moral behavior (Mangla et al., 2021). From the farm to the customer, platforms like IBM Food Trust keep a safe, unchangeable record of every step in the supply chain (Lin, 2019). This transparency increases farmer compensation and customer trust, helping both businesses and society. Blockchain technology may avoid fraud and contamination by verifying that the dairy production techniques match international food hygiene and safety standards.

2.3.6. Livestock Farm Using Renewable Energy

In light of the environmental impact of dairy farming, many farms have converted to solar and wind energy (Solankı & Pal, 2021). These forms of energy provide long-term power while reducing fossil fuel use and carbon emissions. Green energy could substantially lower dairy farm operating costs while preserving the environment. Small-scale solar energy systems can power milking machines, water pumps, and refrigeration units. Biogas digestion systems, automated milking, precision feeding systems, and IoT-enabled animal tracking convert a traditional dairy into a green industry.

2.4. Barriers to Knowledge and Skill

Technological skills are needed for farmers to update their farming operations. Most Bangladeshi farmers utilize conventional methods because they do not have enough advanced training to master modern farming tools. Infrastructure issues like farm utilities like electricity, water, sewerage facilities, and the internet are the key to the farms' ultimate success. Farmers should be aware of their barriers and work individually to resolve them. These problems with infrastructure make it hard to use such complex systems in farming in rural parts of Bangladesh.

2.4.1. Scalability and Customization

Most of the tools we have now were made for commercial dairy farms, and it is still unclear how well they will work on small farms. There has been a dearth of research on how to adapt these resources to the specific requirements, constraints, and economic realities of smaller farms.

2.4.2. Socio-Economic and Cultural Barriers

Individuals in rural Bangladesh encounter significant challenges in utilizing technology due to factors such as traditional gender roles in agriculture and resistance to altering established practices. Limited research has explored the influence of smallholder farmers' cultural and socio-economic contexts on their readiness to adopt new technology. These investigations may contribute to addressing the deficiencies by developing targeted training and support initiatives.

This research gap highlights the significance of examining and developing technological solutions that are affordable, scalable, and culturally appropriate for small-scale dairy farming in Bangladesh. It is essential to explore methods for reducing technology costs, enhancing educational programs for farmers, upgrading rural facilities, and tailoring technologies to meet the unique requirements of small dairy farms in the future. Addressing these gaps can significantly enhance the advancement of sustainable dairy farming in developing nations.

3. Materials and Methods

This study follows the system dynamics and case study method and deploys the Vensim simulation application (version 6.01b) to modify the existing daily operation model. Later, the model incorporates technological input variables in several dairy sub-processes to find better sustainable outcomes. While consulting dairy farmers, farm managers, and policymakers, the multidisciplinary technique gathers and analyzes qualitative and numerical information on productivity, resource consumption, and ecological implications. This methodology allows the researcher to triangulate findings from diverse data sources to explore the research topics and improve the reliability and validity of their possible outcomes. This study quantifies the effects of AI, IoT, and renewable energy on carbon emissions, water use, and milk output. Qualitative approaches reveal the pros and cons of deploying these technologies, enabling industry stakeholders to make realistic suggestions.

This research examines dairy sustainability and technological integration using mixed methods of qualitative and quantitative approaches. This study also adopted purposive and convenience sample techniques to explore necessary information. For the qualitative approach, open-ended and semi-structured interviews were conducted with case farm employees like owners, two farm managers (operational and administrative), and stakeholders (two suppliers and three distributors to explore their perspectives. They were asked what-if questions like how modern technologies like AI and IoT can help them increase their productivity and sustainability. These open-ended interviews extract variable inputs for cattle number, milking time, milk production per cow, daily production, and the like. This study observed their daily reports and ledger to verify their information for the quantitative data, for example, when selling to the market, production ledger, feed intake, waste generations, by-product productions, and unit prices.

Again, this study used primary and secondary data. Primary data were collected using open-ended questions based on semi-structured interviews. The largest dairy farm (Nahar Dairy) was selected as a case farm for this study. This case farm is the largest dairy farm in Bangladesh, and it has been operating its business since 1986. They have a total of 1700 cow heads, including milking cows, calves, heifers, and bulls. An interview with the dairy producer (case farm owner) collected quantitative data on their farming techniques, technological use, and environmental management. This study conducted open-ended interviews to find operational challenges and prospects based on technological innovations. Semi-structured interviews with farm managers, supply chain professionals, and policy-makers provided qualitative insights into sustainable practice attitudes, perceptions, and obstacles. Each interview lasted 1–2 h and was conducted in an informal setting. Secondary data from government papers, academic journals, agricultural databases, and industry publications provided historical and contextual background for this study. These sources provided dairy production trends, environmental standards, and policy frameworks for a complete examination of Bangladesh's dairy sector's sustainability and technology adoption. Moreover, this study conducted several rounds of open-ended interviews with the dairy workers, employees, middlemen, and stakeholders to find the bottlenecks. At the same time, this paper investigated the opportunities to deploy technologies to solve the problems and expedite dairy production to meet the current demands.

Simulation Model Development

First, this study uses the simulation model considering the necessary variables in light of the main dairy process, such as cattle management, milk production, waste generation, by-products from waste, and profit generation. The model variables were then quantified through case industry data and plotted into the simulation model as an average or using random uniform where range data were available from the farm. For instance, we obtained average milk production rather than individual cattle performance in milk production. It was noted that milk products rely on their feed habits, weather, health conditions, water intake, and many other things associated with milking cows' daily production. After numerous trials, the model provided real-life outputs for all 32 variables incorporated in the simulation model. Once the study was satisfied with the model functions in the resulting real-life outputs, the outputs were cross-verified by the farm managers.

Secondly, the model has already incorporated blue-label variables in different processing stages and acquired real-life and technological data from the literature. After a series of discussions with farm representatives, this study quantified the blue-level variables to find potential sustainable outcomes. For example, the variable "Technology for Biogas Conversion" can improve its productivity by close to 129% if the farm uses relevant technologies to convert the waste into biogas. Such positive effects will proceed with the following variables to improve the whole system. After examining all the values, the simulation model runs again to find the total improvements in different areas like mil productions, value additions, by-product increments, and profit generations.

4. Results and Discussions

4.1. Problems, Impact, Remedies, and Technologies

This research considers triple-bottom-line (Arowoshegbe et al., 2016) components (economic, social, and environmental) in light of cutting-edge technological components and applications. Table 2 incorporates the economic problems faced by dairy farms and determines their impacts through farm management opinion by cross-checking available technologies to solve the particular problems. At the same time, the table also explores how these impacts can be mitigated through a particular technology that is being used in different parts of the world. It shows that low milk output, high feed prices, and lack of funding can threaten dairy viability. In Bangladesh, where small-scale farming prevails, these challenges can severely damage dairy farm profitability and viability. Low milk output hurts farmers' profitability and expansion. Improved cow breeds and feed formulas can boost milk output and farm productivity. Automated milking systems with IoT sensors like CowManager and DairyComp 305 can monitor bovine health and modify feeding schedules to boost milk production and cow health.

Table 2. Economic problems, impact, remedies, and technologies.

Problems	Impact	Remedies	Technologies
Low milk yield	Reduces profitability and hinders growth	Introduce improved cattle breeds, use advanced feed formulations	Automated milking systems, IoT sensors, data analytics platforms (e.g., CowManager, DairyComp 305) (Andreen et al., 2021)
High feed costs	Increases production costs and reduces margins	Implement precision feeding systems, develop low-cost feed alternatives	Robotic feeders, precision feeding systems (e.g., Lely Vector, TMR Tracker) (van Erp-van der & Rutter, 2020)
Lack of access to finance	Limits investment in technology and infrastructure	Establish microcredit schemes and provide government subsidies for dairy farmers	Mobile farm management apps (e.g., FarmLogs), digital market platforms (e.g., AgriMarketplace) (Ault et al., 2013)
Inefficient supply chain	Results in wastage and decreased income	Develop cold storage facilities, implement efficient supply chain technologies	Blockchain for supply chain (e.g., IBM Food Trust), cold chain management solution (Mangla et al., 2021)
Lack of market access	Farmers receive low prices due to middlemen	Create direct farmer–market linkages, establish cooperatives	Digital marketplace platforms (e.g., Dairy.com), blockchain for direct transactions (Brush & McIntosh, 2010)
Poor farm management practices	Leads to high operational costs	Provide training programs on farm management and use of technology	IoT sensors for real-time monitoring, farm management software (e.g., AgriWebb) (Kaur & Virk, 2024)
Limited knowledge of modern technologies	Hinders adoption of sustainable practices	Conduct workshops and training programs for farmers on modern dairy technologies	Online training platforms, virtual reality (VR) farming simulators (Yoo & Kim, 2014)

In addition, feed prices increase production expenses and reduce dairy farmer earnings. Lely Vector and TMR Tracker can feed cows nutritionally tailored amounts. This reduces waste and optimizes feed use, saving money. Developing low-cost feed alternatives and robotic feeders can increase economic sustainability by lowering labor and ensuring feed quality. Financial ability is another barrier limiting farmers from investing in infrastructure and modern technology. Government subsidies and microcredit can help farmers overcome this, but such facilities are rare. Dairy farmers can improve their financial strength by making smart choices to protect their operations with the help of modern technologies. Table 3 incorporates the social problems faced by dairy farms and determines their impacts through farm management opinion by validating available technologies to solve the specific problems. Table 3 lists the social sustainability issues of the dairy business, which is compromised by child labor, inadequate working conditions, and limited access to veterinary care, negatively impacting the welfare of farmers, production efficiency, and community development. In rural areas, children are frequently a source of labor on dairy farms, jeopardizing their education, an issue that may be remedied with stricter labor restrictions. Substandard working conditions decrease worker productivity and cause health hazards, which could be addressed by improving infrastructure by utilizing IoT-based farm monitoring systems alongside advanced temperature control technologies. For example, BFN Fusion from Big Dutchman optimizes work settings, a modern technology that can markedly boost labor efficiency and optimize overall farming operations.

Table 3. Social problems, impact, remedies, and technologies.

Problems	Impacts	Remedies	Technologies
Child labor in dairy farms (Ramos, 2021)	Affects child education and welfare	Implement child education programs, enforce labor laws	E-learning platforms, mobile education apps
Poor working conditions (Wijers, 2019)	Reduces labor productivity and health	Improve farm facilities and provide worker safety training	IoT sensors for monitoring barn conditions, smart climate control systems (e.g., Big Dutchman)
Lack of veterinary services (Van der Leek, 2015)	Results in poor animal health and loss of livestock	Increase availability of veterinary services, set up mobile vet clinics	Telemedicine for livestock, IoT livestock health monitors (e.g., SCR Heatime Pro)
Gender inequality (Wijers, 2019)	Limits women's involvement in dairy farming	Promote women's participation through training and credit facilities	Mobile financial apps, online training and support platforms
Inadequate farmer education (Quddus, 2018)	This leads to traditional, less efficient practices	Provide farmer education on sustainable practices through government and NGO programs	Online learning platforms (e.g., Udemy, Coursera), mobile farm management apps
Social stigma around dairy farming (Shortall et al., 2018)	Limits workforce and youth interest	Promote dairy farming as a profitable and dignified profession	Social media platforms for awareness, farm management simulation games
Limited access to health services (Wijers, 2019)	It affects farmers' well-being and productivity	Establish health care support programs for farming communities	Telemedicine apps, health monitoring wearables for farmers

Also, the absence of veterinary services is a major issue that frequently results in an overall decrease in animal health and cattle fatalities, affecting the livelihoods of dairy farmers. Improving the availability of veterinary care and establishing mobile veterinarian clinics are viable alternatives. Technologies like telemedicine for livestock and IoT health monitors (e.g., SCR Heatime Pro) provide continuous tracking of livestock health and allow for remote discussions with veterinarians. This allows for timely medical care and improved livestock management, which are crucial to sustaining dairy herd health and increasing farm profitability. Confronting these social sustainability concerns will enable the dairy business to enhance the quality of life for farmers, workers, and their communities.

Table 4 incorporates the economic problems confronted by dairy farms and determines their impacts through farm management opinion by verifying available know-how to solve specific problems. Table 4 lists the environmental challenges regarding farms' environmental and financial future, predominantly caused by ineffective supply networks, backdated production methods, poor genetics, improved cross-breed development, inadequate manure management, overuse of water, water contamination, and higher emissions of greenhouse gases. Poor manure management leads to soil and water contamination, posing risks to local ecosystems and community health. Systems like AgriSep and biogas digesters convert manure into energy or fertilizers, reducing hazards and boosting revenue. It will also reduce environmental hazards and increase farm revenues, which help them to develop the latest technologies in other efficient areas. Using the reverse supply chain and circular economy theory, such practices will help convert waste into valuable resources.

Table 4. Environmental problems, impact, remedies, and technologies.

Problems	Impacts	Remedies	Technologies
Improper Manure Management	Causes soil and water pollution	Implement manure management systems, use manure as biofertilizer	Biogas digesters (e.g., PlanET Biogas), manure management systems (e.g., AgriSep) (Pandey et al., 2021)
Excessive Water Use	Depletes local water resources	Adopt water-efficient farming practices, use automated watering systems	IoT-enabled water management systems (e.g., AquaSpy, CropX) (Akbar et al., 2020)
Greenhouse Gas Emissions	Contributes to climate change	Introduce renewable energy systems that use feed additives to reduce methane emissions	Renewable energy systems (solar panels, wind turbines), AI-based emission monitoring (Minoofar et al., 2023)
Overgrazing	Leads to land degradation and soil erosion	Implement rotational grazing practices, establish virtual fencing	Virtual fencing (e.g., Vence, Agersens eShepherd), GPS-based grazing management (Verdon et al., 2021)
Use of Chemical Fertilizers	Causes soil and water contamination	Promote organic farming, use precision agriculture tools	Precision agriculture tools, IoT soil sensors, drones for precision spraying
Poor Waste Disposal	Causes environmental pollution	Develop waste recycling and disposal systems, establish biogas digesters	Biogas digesters, waste recycling machinery (Pandey et al., 2021)
Loss of Biodiversity	Affects ecosystem health and resilience	Implement agroforestry, promote biodiversity-friendly farming practices	Drones for ecosystem monitoring, IoT sensors for biodiversity tracking (Herlin et al., 2021)

Dairy farms must adequately manage water resources, particularly in drought-prone areas. Conventional dairy farming requires plenty of water for animals' hydration, hygiene, and irrigation, straining the local water supply. IoT-enabled water management methods like AquaSpy and CropX provide real-time moisture level data and synchronize irrigation timing to fulfill crop and animal demands. These innovations could decrease water use by 20–30%, boosting the economics of farming and sustainability. These approaches reduce water expenses, protect the health of the soil, and lower the risk of shortages of water that could disrupt farming operations for dairy manufacturers.

Dairy farms substantially contribute to global climate change, mainly through methane gas emissions from cattle produce. Applying renewable energy systems such as solar panels and wind turbines can effectively decrease dependency on petroleum and coal and mitigate carbon dioxide emissions. Likewise, applying feed additives to reduce methane emissions in grazing animals and utilizing AI-driven emission monitoring technologies facilitates more accurate tracking and mitigation of greenhouse gases. For instance, smart technologies like rotational grazing and eShepherd reduce overgrazing and improve ecosystems. These strategies reduce the environmental footprint of dairy farms while enhancing operational efficiency and sustainability, allowing the dairy sector to contribute to global climate goals. The above discussion undoubtedly demonstrated triple-bottom-line implications for a dairy farm based on technological implications. Such information will help the farmers and stakeholders understand the technical benefits of achieving more profits and utilizing their unused resources as valuable by-products.

4.2. Simulation Model on a Case Dairy Farm

This study extended the Shamsuddoha et al. (2023a) simulation model to determine sustainable benefits based on the triple-bottom-line theory (Arowoshegbe et al., 2016). Figure 2 demonstrates the main functional variables of dairy: production of milk, generation of waste, by-product production, revenue generation, cattle, mature cattle, and culled cows after aging. To achieve sustainable outcomes, this research includes blue-level technological variables within the model, according to the opinion of the case industry. Numerous runs through the simulation model using different settings have been investigated to identify improvements in by-product generation, waste reductions, and profitability. This model supports comprehending what-if scenarios through numerous trials to determine prospective benchmark scenarios for achieving sustainable objectives. The model was extended by adding innovative technology variables (blue-level) and measures through probability theories (value between 0 and 1). These variables used a random uniform statistical formula using probabilistic assumptions. These assumptions are based on farm experience and facility providers, such as 10–15% milking, which can be increased if an automated milk parlor system is deployed in the farm operation.

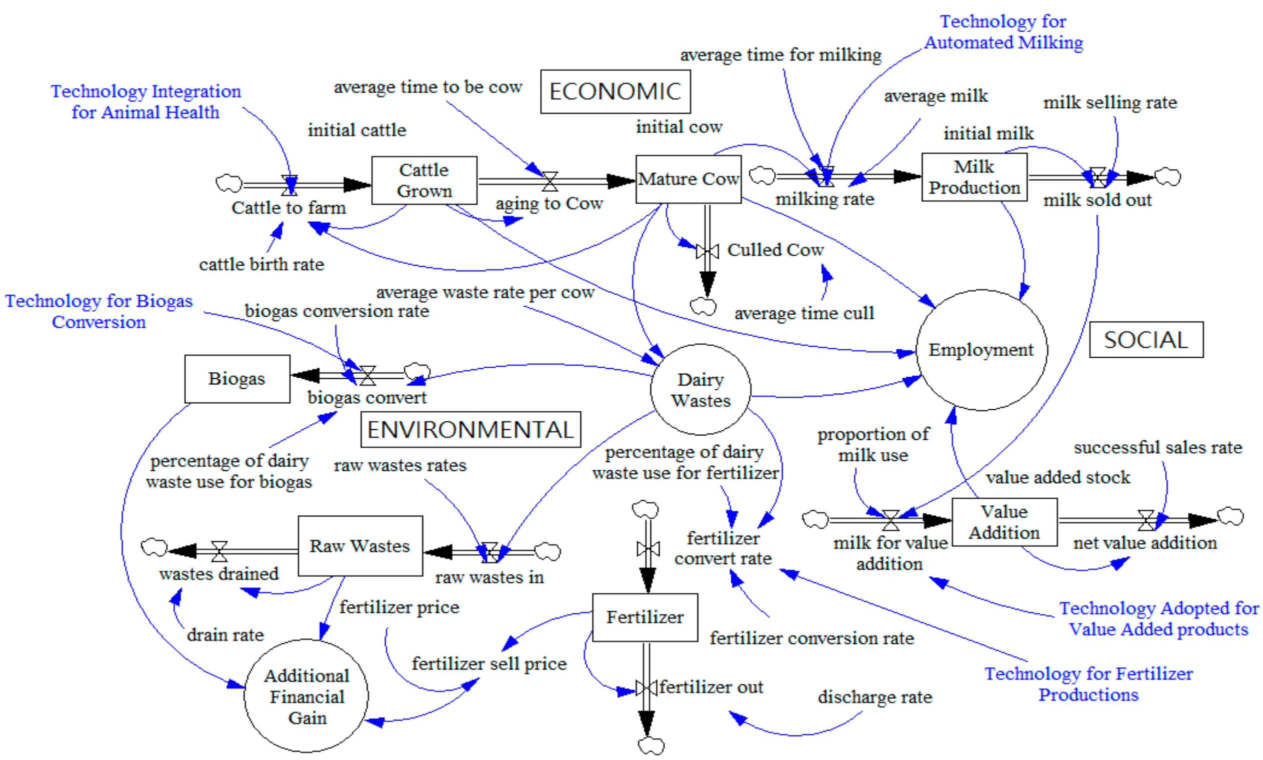

Figure 2. A simulation model for a dairy farm.

Figure 2 is a revised model incorporating blue-marked variables in different sub-processes, estimating productivity and efficiency improvements. Later, simulation runs with numerous trials are compared between current and simulated results and the intent to find sustainable outcomes. To develop the above simulation model, this study incorporated 32 variables, namely "Cattle Grown", "Mature Cow", "Culled Cow", "Milk Production", "Milk Sold Out", "Biogas", "Dairy Wastes", "Raw Wastes", and "Fertilizer". According to the case farm representatives, these are the key components of the dairy process. Table 5 demonstrates the key variables and their numerical values originating from the dairy farm case. The right-hand column represents units for key variables listed in the same table. The simulation model runs for 60 months, and all the numerical values are converted monthly. For example, the average milking per cow is 210.09 L per cow monthly. Obviously, a milking cow house contains all sorts of milking cows based on their average milking cycle of 12 months per cow. The closer to the end of the milking cycle, the less milk the cow will release, whereas more will be produced early during the milking cycle and during the middle of the milking cycle. Thus, it is the average output of all milking cows, not counting the highest and lowest yields.

Table 5. Key variables, and their values and units.

SL	Variables	Value	Unit
1	Age of Cow	55.56	Months/Cow
2	Average Milk	210.09	Liters/Month
3	Average Time for Culling	72	Months/Cow
4	Average Time for Milking	12	Months/Cow
5	Average Time to be Cow	18	Months/Cow
6	Average Waste Rate per Cow	0.5692	Tons/Month
7	Cattle Birth Rate	0.06	Dimensionless
8	Cattle to Farm	13.83	Months/Cow
9	Culled Cow	2.778	Cows/Month
10	Dairy Wastes	113.84	Tons/Month
11	Employment	95.69	Persons/Month
12	Fertilizer Convert Rate	0.3	Dimensionless
13	Fertilizer Conversion Rate	12.68	Percentage
14	Fertilizer Price	37.83	Dollars/Ton
15	Initial Cattle	200	Cows
16	Initial Cow	200	Cows
17	Mature Cow	200	Cows
18	Cattle to Farm	13.83	Cows/Month
19	Milking Rate	4052	Liters/Month
20	Percentage of Dairy Waste Used for Biogas	0.15	Percentage

4.3. Achieve Triple-Bottom-Line of Sustainability Through Technological Advancement

To achieve sustainable outcomes with more productivity and efficiency, this study searches for relevant technologies available in the marketplace to solve each problem. Tables 6–9 integrate particular technologies and their purpose/uses to increase productivity. Table 6 lists the relevant technologies that solve multiple economic, social, and environmental sustainability challenges.

Table 7 also lists marketplace applications or technologies that can be deployed immediately to obtain better results. These technologies are popular with existing farms located in dairy-developed nations. For example, virtual fencing technologies (Vence, Agersens, and eShepherd) can help farms manage their livestock grazing sustainably. Such grazing technology helps the farm achieve economic and environmental outcomes. Table 7 listed the appropriate technologies related to the economic success of a dairy farm. For example, robotic feeders can automatically feed livestock, reducing waste and costs. Due to inflation and expensive feed ingredients, the feed costs are high now. Such technology will help the farm save on costs and labor.

Table 6. Triple-bottom-line success through technology.

Technology	Uses	Tools/Apps
Virtual Fencing (Verdon et al., 2021)	Manages livestock grazing sustainably (environmental, economic)	Vence, Agersens, eShepherd
IoT Sensors (Tangorra et al., 2024)	Monitors livestock health and improves welfare (social, economic)	CowManager, Allflex Livestock Monitoring
Renewable Energy Systems (Minoofar et al., 2023)	Reduces carbon footprint and energy costs (environmental, economic)	Solar Panels, Wind Turbines
Digital Market Platforms (Kulish et al., 2024)	Connects farmers with buyers, ensuring fair trade (economic, social)	AgriMarketplace, Dairy.com
Automated Calf Feeders (Hnatiuc & Caracostea, 2017)	Ensures optimal nutrition for calves (economic, social)	Förster-Technik, Holm & Laue Calf Feeder
Precision Feeding Systems (Liu et al., 2023)	Provides accurate feeding to reduce waste (economic, environmental)	Lely Vector, TMR Tracker
Mobile Farm Management Apps (Barrios et al., 2023)	Helps in monitoring and managing farm operations	FarmLogs, AgriWebb

Table 7. Economic success through technology.

Technology	Uses	Tools/Apps
Robotic Feeders (Mikhailichenko, 2023)	Automates feeding, reducing waste and costs (economic)	Trioliet Triomatic, DeLaval Optimat
Automated Milking Systems (Hansen et al., 2020)	Reduces labor costs and increases milk yield (economic)	Lely Astronaut, GEA DairyRobot R9500
Artificial Intelligence (AI) (Fuentes et al., 2020; Sodhi et al., 2017)	Enhances animal health predictions, reducing losses (economic)	Cainthus, Connecterra
Data Analytics Platforms (Cabrera & Fadul-Pacheco, 2021)	Optimizes production efficiency (economic)	DairyComp 305, BoviSync
Genomic Selection Tools (Wiggans et al., 2017)	Improves breeding practices for productivity (economic)	Zoetis CLARIFIDE, Neogen Igenity
Automated Milking Systems (Hansen et al., 2020)	Improves efficiency and reduces labor costs	Lely Astronaut, GEA DairyRobot R9500

Table 8. Social success through technology.

Technology	Uses	Examples of Tools/Apps
Blockchain Technology (Mangla et al., 2021)	Ensures supply transparency and traceability (social)	IBM Food Trust, VeChain
Smart Climate Control Systems (Nleya & Ndlovu, 2021)	Maintains optimal barn conditions, improving animal welfare (social)	Smart Barn, Big Dutchman Climate Control
RFID Technology (Trevarthen & Michael, 2007)	Tracks animal movement and health, ensuring welfare (social)	SCR Heatime Pro, Nedap CowControl

Table 9. Environmental success through technology.

Technology	Uses	Examples of Tools/Apps
Drones (Heins et al., 2023)	Monitors crop health and optimizes fertilizer use (environmental)	DJI Agras, Sentera FieldAgent
GPS Technology (Hofmann, 2024)	Manages field operations to reduce input costs (environmental)	John Deere GreenStar, Trimble AgGPS
Water Management Systems (Kominami & Lovell, 2012)	Optimizes water usage, conserving resources (environmental)	AquaSpy, CropX
Biogas Digesters (Pandey et al., 2021)	Converts manure to renewable energy, reducing waste (environmental)	BIOGAS24, PlanET Biogastechnik
Manure Management Systems (Niles et al., 2022)	Treats manure for use as fertilizer (environmental)	AgriSep, GEA Manure Management Solutions
Carbon Footprint Calculators (Sukhoveeva, 2021)	Monitors and minimizes greenhouse gas emissions (environmental)	Cool Farm Tool, Agrecalc
IoT Sensors (Nleya & Ndlovu, 2021)	Monitors livestock health and environmental conditions	CowManager, Allflex Livestock Monitoring

Similarly, Table 8 states the appropriate technologies related to the social success of a dairy farm. For example, blockchain technology ensures transparency and traceability using smart technologies like IBM Food Trust and VeChain. Blockchain technology also boosts customer trust and social sustainability. Furthermore, digital market platforms like AgriMarketplace and Dairy.com allow farmers to connect with buyers directly, eliminating intermediaries and ensuring fair trade, increasing farmer revenues by 10–15%.

Likewise, Table 9 states the appropriate technologies related to the environmental success of a dairy farm. For example, drone technology can monitor livestock and crop health and optimize fertilizer usage, which can directly help with environmental upgrades. Modern dairy farming could potentially be sustainable economically, socially, and environmentally. The Lely Astronaut (Lely North America, Pella, IA, USA) and GEA DairyRobot R9500 (GEA United States, Columbia, MD, USA) automatic milking devices reduce labor costs and increase milk production, enhancing economic sustainability. Such devices can boost milk production by 10–15% while lowering labor costs by 30–40%, thus improving the profitability of dairy producers.

On the other hand, IoT devices like CowManager and Allflex Animal Monitoring monitor animal health and the environment, providing several advantages. These sensors identify illnesses early and improve feeding regimens, lowering veterinary expenses and boosting animal well-being. Platforms like DairyComp 305 may evaluate sensor data to improve production efficiency and minimize operating expenses. IoT and data analytics cut feed loss by 20%, benefiting the environment and economy. Biogas digesters (e.g., BIOGAS24, PlanET Biogastechnik) turn manure into renewable energy, lowering greenhouse gas emissions and providing farmers with additional energy. Biogas digesters may cut methane emissions by 50% and save farms 15–20% in energy expenses. Thus, with this modern technology, dairy farming can develop sustainability while reducing environmental impact and improving social welfare.

Based on the above discussion (from Tables 6–9), we have thoroughly discussed each technological component with the case farm entrepreneur and farm managers to find possible implementations for increasing productivity, efficiency, and sustainability. The interviewee is well informed about most of the technologies, but at the same time, they are aware of their limitations on budget constraints and lack of applicability. For example, farmers are aware of robotic feed allocation but disagree with implementing such technologies, as Bangladesh is a cheap labor country. Thus, they prefer to stick to human labor. However, they have already found utilities from automated milking parlors and precious feed productions. Automated water and waste management, smart cattle belts (IoT), automated lab tests, and many other technologies exist presently. At the same time, they want to incorporate more in the coming days and expect more benefits. For instance, they want to invest in more advanced waste management technologies to convert them into electricity, biogas, and bio-fertilizers. The farm is also interested in investing in renewable energy to become self-dependent as the government power supply is inconsistent. Table 10 is the outcome of the in-depth discussions focusing on the blue-level technological variables and finding potential better outcomes for dairy farms.

Table 10. Probabilistic productivity using smart technology.

SL	Variables	Value	Unit	Possible Increment/ Productivity
1	Technology Integration for Animal Health	1.152	Percentage	115.2
2	Technology for Automated Milking	1.157	Percentage	115.7
3	Technology for Fertilizer Productions	1.238	Percentage	123.8
4	Technology for Biogas Conversion	1.291	Percentage	129.1
5	Technology Adopted for Value-Added Products	1.314	Percentage	131.4

The above table shows the blue-label variables and their prospective output values, unit names, and possible increments in the various dairy sub-processing stages. For example, if "Technology Integration for Animal Health" is deployed on a farm, cattle health will improve by up to 15.20%. Installing smart IoT belts, precision feeders, and automated lab tests can help the farm protect their cows' health, and save unnecessary treatment costs. This device also decreases disease rate, improves production times, and improves milk productivity. This study considered the farmers' opinions based on each technological vendor's promises through product promotions.

4.4. Simulation Results

Different data sets were simulated in this study, with the two runs named "current" and "technology adoption". The first run of the simulation model outputs was similar to the current dairy operational outputs for the case dairy farm. This study used a simple validation process by extracting farm data (output) for each stock variable, such as cattle, mature cattle, waste, and the like, and replicating the same output in the model environment. For example, the model used one house of 200 cattle and mature cows, producing roughly 3500 L of milk daily. Similar information was used to validate the real-life productions and model output. Once the model replicated the actual farm process and its output, technological variables were added in various stages to expect more efficiency and productivity. The second run is based on technological innovations and, as discussed above, how these technologies assist the farmers in having more utilities and profitability. The modified simulation runs positive results, obtaining sustainable outcomes. The figures below are the primary outcomes of the study, which validate technological deployments if a farm can do so. It will undoubtedly boost their sustainable outcomes and efficiency.

Figure 3 demonstrates the "milk production" and "dairy wastes" variables of a case farm of Nahar dairy. It is clearly visible that the blue line (simulated results with technological implications) performs better than the red line (current operation). For instance, automated milk parlors boost productivity by 10–15% and reduce mastitis in cows. Consequently, fewer cows died, and livestock numbers increased over time. Such an increase in the flock will generate more waste and help produce by-products like biogas, organic fertilizers, and artificial charcoal.

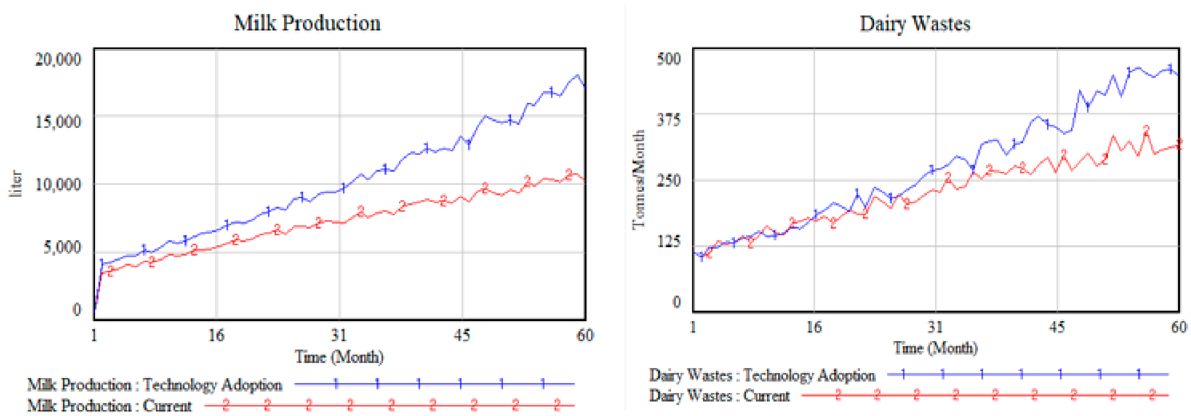

Figure 3. Simulated results for "milk production" and "dairy wastes".

Figure 4 demonstrates the "fertilizer" and "biogas" variables of a case farm, and it is evident that the blue line (simulated results with technological implications) has better performance than the red line (current operation). For instance, more waste can generate more fertilizer and biogas. More fertilizer helps the farm to increase crop management surrounding their property. On the other hand, biogas can help them generate sustainable energy for farms and surrounding areas.

Figure 5 demonstrates the "employment" and "additional financial gain" variables of a case farm, and it is evident that the blue line (simulated results with technological implications) has better performance than the red line (current operation). Technological implementation could be assumed to eliminate employment, but the simulated results show the opposite. This research looked at it in depth and found that the employment increment is logical. For instance, more fertilizer will encourage the farmer to add more crops in their surrounding vacant lands, and livestock numbers will increase due to less casualty for technology usage. Such herd growth, additional crop management, and waste management will help the farmers create more employment, which can contribute socially.

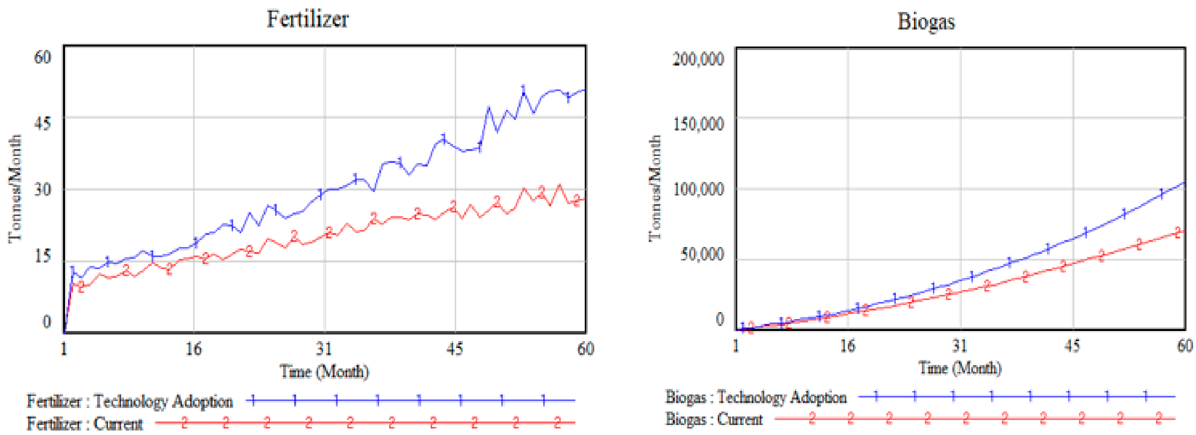

Figure 4. Simulated results for "fertilizer" and "biogas generation".

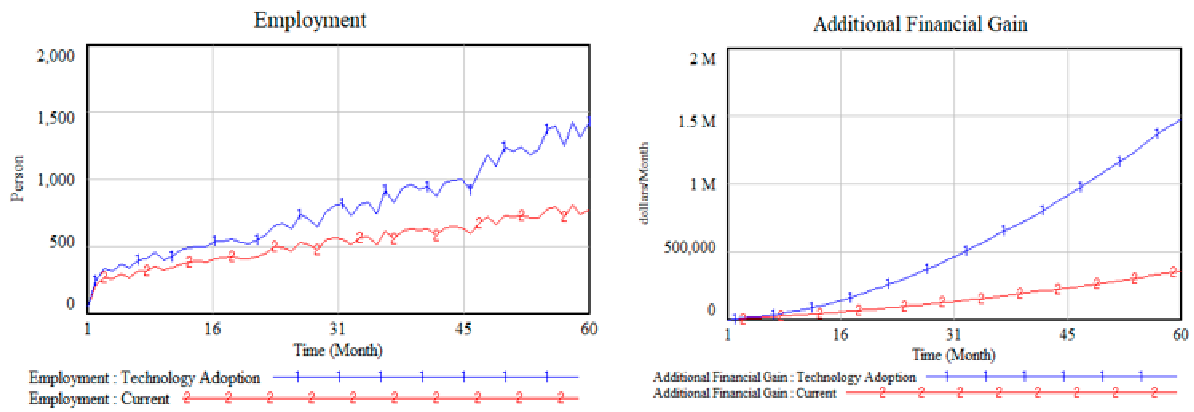

Figure 5. Simulated results for "employment creation" and "financial gains".

Comparative Results for the Key Variables

Tables 9 and 10 below show comparative results between the simulated and actual models. Based on the current livestock numbers, the simulation runs for 60 months (5 years). The results clearly show sustainable growth in five years. Table 11 demonstrates various results comparing current and technologically adopted processes. It is evident that technological adoption will be a blessing for the farm as the outputs are significantly more significant than the current process. For instance, the "Financial Gains" will be USD 1.481 million after five years, whereas the current process could earn roughly USD 354,678. Apparently, there will be huge investment repayments for the farms if they decide to adopt modern technological equipment.

Table 12 also shows the statistical comparison between the current and technology-adopted simulated models. The table demonstrates the mean, median, standard deviation, and norm. The table demonstrates a clear advantageous position for the farm when they decided to adopt these technologies into their processes.

The above results and discussions are evident enough that technology can positively transform the dairy farms in Bangladesh. A developed country can extract more than 40 L of milk per cow daily, whereas local farms can extract an average of 2–5 L. This information highlights that Bangladeshi farmers are the key stakeholders to engage with in order to achieve such a benchmark. It is possible that they will start adopting technology for efficient farm management and continuous breed development.

Table 11. Comparative simulated results for the key variables.

Time (Month)	1	10	20	30	40	50	60
Additional Financial Gain (USD)	4755	68,471	220,607	448,053	737,062	1.085 M	1.481 M
Current (USD)	3797	32,338	77,155	132,495	196,426	272,209	354,678
Biogas (Tonnes)	837.11	13,224	43,401	88,484	146,280	215,404	294,403
Current (Tonnes)	648.5	6290	15,222	26,246	38,979	54,094	70,550
Employment (No.)	282.6	906.15	1510	2458	2793	3549	3791
Current (No.)	209.39	321.44	403.45	560.47	617.62	724.59	777.02
Fertilizer (Tonnes)	12.68	38.61	64.28	88.11	99.72	120.38	135.69
Current (Tonnes)	10.25	12.99	16.31	19.96	23.66	27.21	28.03
Milk Production (Liter)	4052	12,939	21,196	28,877	37,142	41,852	45,228
Current (Liter)	3501	4841	5952	7200	8696	9199	10,130
Value Addition (Liter)	220.75	3201	6360	16,994	14,970	24,838	26,082
Current (Liter)	172.42	944.25	1359	3132	2657	4219	4224

Table 12. Statistical comparison between the "technology adopted" and "current" models.

Variable	Max	Mean	Median	StDev	(Norm)
Additional Financial Gain Technology Adoption:	1.481 M	557,811	462,742	452,682	0.8115
Current:	354,678	150,144	135,196	105,343	0.7016
Biogas; Technology Adoption:	294,403	110,580	91,422	90,075	0.8146
Current:	70,550	29,772	26,781	20,991	0.7051
Dairy Wastes; Technology Adoption:	1278	771.02	824.86	345.79	0.4485
Current:	343.07	226.2	229.66	64.61	0.2856
Employment; Technology Adoption:	3853	2200	2302	1033	0.4694
Current:	806.99	520.8	537.36	166.89	0.3204
Fertilizer; Technology Adoption:	142.13	82.98	89.15	39.18	0.4722
Current:	30.88	19.88	20.29	6.276	0.3156
Milk Production; Technology Adoption:	48,625	28,317	29,386	13,129	0.4637
Current:	10,706	7156	7255	2241	0.3132
Value Addition; Technology Adoption:	26,082	12,508	13,188	6974	0.5576
Current:	4373	2389	2473	1000	0.4187

5. Recommendations

The above discussions on triple-bottom-line components, relevant technologies, and simulation results were communicated to the case farm representatives. This study identified many recommendations but kept important agendas for the policy, technological, and farm-level recommendations for the gradual development of Bangladeshi dairy farms. These strategies collectively contribute to a more sustainable and efficient dairy industry by fostering technological integration, improving farmer education, and offering financial incentives. Moreover, transformation is rapid, so farm owners must be vigilant about the latest technologies if they delay implementing the agendas below.

5.1. Policy Recommendations

1. Support for waste management systems: To improve the sustainability of dairy production, policy measures should promote the implementation of waste management systems for producing by-products from unused wastes that cause environmental hazards. For example, farm-produced raw dung can be converted into biogas, bio-fertilizers, and artificial charcoal to burn organic components for the village household. Such by-products will generate revenues and minimize waste. This simulation model can be useful for assessing operational activities before jumping out to find profitability and economic scale. To implement the above, policymakers need to highlight the benefits and help learn the procedures for the transformation.
2. Financial incentives: Most dairy farm owners are not financially sound enough to implement all the changes, although they know the benefits of using transformation. In these circumstances, governments, NGOs, and banks can offer incentives for adopting smart technologies. Microcredit schemes and tax incentives should be implemented to promote investments in environmentally favorable innovations, resulting in enhanced social, environmental, and economic outcomes for dairy farms.
3. Educational initiatives: Knowledge and understanding are the main aspects before implementing any changes, as changes may not work as planned and expected. Relevant parties can arrange a series of educational and training sessions for the farmers and stakeholders to understand what they need to transform. Implementing government-sponsored programs focusing on sustainable agricultural practices and technological advancements is essential for providing producers with the requisite skills. For example, The Department of Youth Development has frequently arranged sessions since the 1980s, and it has helped many youths to become agricultural entrepreneurs in the last four decades.
4. Virtual marketplaces: Implement virtual marketplace platforms to diminish the necessity of intermediaries, thereby enhancing farmers' direct access to a broader range of markets and equitable pricing for additionally produced by-products of biogas, bio-fertilizers, and slurries. The end customers constantly complain about middlemen as they absorb most of the costs, resulting in farmers are not making enough on their products. In this scenario, the virtual or digital marketplace can help the customers and producers reduce middlemen and farm product prices.

5.2. Technology Recommendations

Advanced technology and education improve dairy farm's environmental, economic, and social impacts.

1. Biogas digesters: Biogas digesters use AI-driven solutions to reduce carbon emissions and manage manure, promoting environmental sustainability.
2. Water management optimization: Use IoT-enabled water management systems to improve dairy water consumption efficiency.
3. Enhance productivity (waste by-products) and market access: Increase productivity using precision feeding systems and improve waste by-products (fertilizer, biogas, and slurry) to obtain better market access to agricultural farmers and reduce chemical usage in their crop fields.
4. Social sustainability improvements: Telemedicine for veterinary care and online learning platforms can teach farmers technologies to improve social sustainability in the dairy industry.

5.3. Practical (Farm-Level) Recommendations

The integration of financial aid, knowledge dissemination, and digital technologies for operational efficiency improves dairy sustainability.

1. Support technology adoption: Consider technologies for milk parlors, preservations, precise feed management, waste management, and renewable energy.
2. Educational seminars: Teach employees vital skills through daily briefing/weekly/monthly workshops on sustainable practices, new technology, and farm management.
3. Promote mobile farm management software and internet platforms to identify cattle health and implement tele-veterinary services 24/7 to reduce disease impacts.

The above discussions and model outputs addressed the study objectives of how cutting-edge technologies like IoT, AI, and renewable energy enhance sustainability and efficiency in dairy operations in Bangladesh. Utilizing the triple-bottom-line framework, it meticulously evaluates the social, environmental, and economic implications of these advancements, highlighting achievements in profitability, efficiency of resources, and restoration of the environment. In addition, this study provides an overall strategy for integrating modern technologies into dairy operations. It provides feasible recommendations for farmers, stakeholders, and policymakers to support efficient and environmentally friendly dairy farming techniques.

6. Conclusions

This study examines the integration of advanced technologies such as AI, ML, IoT, robotics, and renewable energy to enhance efficiency and sustainability in Bangladeshi dairy operations. The findings highlight the substantial benefits of cutting-edge technologies and innovations to improve process quality and productivity, reduce waste, utilize abundant resources, and ensure financial resilience in the dairy farm. Utilizing a case-specific simulation model, this research validates how integrating technological resolutions can transform critical obstacles like waste management and operational inefficiencies. By incorporating these technologies, dairy farms can minimize waste and enhance animal health, consequently increasing profitability and reducing the adverse environmental effects. Biogas digesters economically eliminate waste to generate sustainable energy, increasing financial capacity. The research shows that incorporating such technologies into the dairy manufacturing process could improve sustainability, particularly in countries like Bangladesh, where conventional farming practices often result in environmental degradation. This study also points out whether strategic planning structures successfully helped farmers and stakeholders implement modern technologies for environmentally friendly practices. These findings provided practical recommendations for dairy producers, policymakers, and industry partners aiming to support sustainable and technologically sophisticated dairy operations. Nevertheless, the research was limited to a case farm, though the case farm is the largest dairy farm in Bangladesh. Many farms are located in remote and peri-urban areas of Bangladesh and do not even have minimum technology usage. Real-time data regarding technology use in the dairy sector were sparse in the local context; thus, this study used qualitative observations and case data to simulate the results as an ideal farm. Adopting up-to-date technologies in the dairy sector is notably behind due to insufficient modern infrastructure, lack of profitability leads, and inadequate farmer knowledge of recent developments. This limitation may not adequately represent the complicated nature of all types of dairy farms and their supply networks. In order to obtain more comprehensive insights, future research could employ larger sample sizes and cover rural, urban, and peri-urban areas as well as primary quantitative data. Moreover, integrating real-time data from advanced monitoring systems can enhance the accuracy and applicability of simulation models.

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References

Adams, C., Frost, G., & Webber, W. (2013). Triple bottom line: A review of the literature. In *The triple bottom line* (pp. 17–25). Routledge.

Akbar, M. O., Shahbaz khan, M. S., Ali, M. J., Hussain, A., Qaiser, G., Pasha, M., Missen, M. S., & Akhtar, N. (2020). IoT for development of smart dairy farming. *Journal of Food Quality*, *2020*(1), 4242805. [CrossRef]

Andreen, D., Haan, M., Dechow, C., & Harvatine, K. (2021). Determination of relationships between rumination and milk fat concentration and fatty acid profile using data from commercial rumination sensing systems. *Journal of Dairy Science*, *104*(8), 8901–8917. [CrossRef]

Arowoshegbe, A. O., Emmanuel, U., & Gina, A. (2016). Sustainability and triple bottom line: An overview of two interrelated concepts. *Igbinedion University Journal of Accounting*, *2*(16), 88–126.

Ault, A. C., Krogmeier, J. V., & Buckmaster, D. (2013, July 21–24). *Mobile, cloud-based farm management: A case study with trello on my farm*. Paper presented at the An ASABE Meeting Presentation, Kansas City, MO, USA.

Bangladesh Bureau of Statistics (BBS). (2023). *Agricultural statistics*; Bangladesh Bureau of Statistics.

Barrios, D., Olivera-Angel, M., & Palacio, L. G. (2023). Factors associated with the adoption of mobile applications (Apps) for the management of dairy herds. *Revista de Economia e Sociologia Rural*, *61*, e264382. [CrossRef]

Beldman, A., Lesschen, J., Vellinga, T., Komleh, H. P., Boone, K., Blonk, H., & Scholten, J. (2021). *Developing GHG mitigation strategies for agro-sectors: Feasibility study for the dairy sector*. Wageningen Economic Research.

Bhoj, S., Tarafdar, A., Singh, M., & Gaur, G. (2022). Smart and automatic milking systems: Benefits and prospects. In *Smart and sustainable food technologies* (pp. 87–121). Springer.

Bhusal, D., & Thakur, D. P. (2022). Precision nitrogen management on crop production: A review. *Archives of Agriculture and Environmental Science*, *7*(2), 267–271. [CrossRef]

Bicak, N., Alduaylij, S., Al-Maamari, N., Beekman, D., Belgum, K., Chubb, L., Forte, N., Hill, M., Holstein, J., Lambe, D., & Le, P. (2022). *Interdisciplinary design studio: Programming document visioning for a robotic demonstration, research, and engagement dairy*. Available online: https://digitalcommons.unl.edu/archstucreact/2 (accessed on 18 September 2024).

Bin Duwa bin Khoja, D. A. (2021). Participation of rural women in agricultural activities. *International Journal of Modern Agriculture and Environment*, *1*(2), 1–25. [CrossRef]

Brush, G. J., & McIntosh, D. (2010). Factors influencing e-marketplace adoption in agricultural micro-enterprises. *International Journal of Electronic Business*, *8*(4–5), 405–432. [CrossRef]

Cabrera, V. E., & Fadul-Pacheco, L. (2021). Future of dairy farming from the Dairy Brain perspective: Data integration, analytics, and applications. *International Dairy Journal*, *121*, 105069. [CrossRef]

Czekała, W. (2022). Biogas as a sustainable and renewable energy source. In *Clean fuels for mobility* (pp. 201–214). Springer.

Datta, A. K., Haider, M. Z., & Ghosh, S. K. (2019). Economic analysis of dairy farming in Bangladesh. *Tropical Animal Health and Production*, *51*, 55–64. [CrossRef] [PubMed]

Department of Livestock Services (DLS). (2023). *Livestock economy at a glance (livestock population of Bangladesh)*. Available online: https://dls.gov.bd/site/page/22b1143b-9323-44f8-bfd8-647087828c9b/Livestock-Economy (accessed on 29 December 2024).

Feil, A. A., Schreiber, D., Haetinger, C., Haberkamp, Â. M., Kist, J. I., Rempel, C., Maehler, A. E., Gomes, M. C., & da Silva, G. R. (2020). Sustainability in the dairy industry: A systematic literature review. *Environmental Science and Pollution Research*, *27*, 33527–33542. [CrossRef]

Fuentes, S., Gonzalez Viejo, C., Cullen, B., Tongson, E., Chauhan, S. S., & Dunshea, F. R. (2020). Artificial intelligence applied to a robotic dairy farm to model milk productivity and quality based on cow data and daily environmental parameters. *Sensors*, *20*(10), 2975. [CrossRef] [PubMed]

Garcia, S. N., Osburn, B. I., & Cullor, J. S. (2019). A one health perspective on dairy production and dairy food safety. *One Health*, *7*, 100086. [CrossRef] [PubMed]

Gazi, M. A. I. (2020). Supply chain management for agro products in Bangladesh; logistics support for capturing market by ensuring balanced distribution. *International Journal of Management, Accounting and Economics*, *7*(6), 277–297.

Gerosa, S., & Skoet, J. (2012). *Milk availability: Trends in production and demand and medium-term outlook*. Available online: https://ageconsearch.umn.edu/record/289000 (accessed on 9 February 2024).

Gheorghe-Irimia, R. A., Sonea, C., Tapaloaga, D., Gurau, M. R., Ilie, L.-I., & Tapaloaga, P.-R. (2023). Innovations in Dairy Cattle Management: Enhancing Productivity and Environmental Sustainability. Annals of" Valahia" University of Târgovişte. *Agriculture*, *15*(2), 18–25. [CrossRef]

Hansen, B. G., Bugge, C. T., & Skibrek, P. K. (2020). Automatic milking systems and farmer wellbeing–exploring the effects of automation and digitalization in dairy farming. *Journal of Rural Studies*, *80*, 469–480. [CrossRef]

Harrington, L. M. B. (2016). Sustainability theory and conceptual considerations: A review of key ideas for sustainability, and the rural context. *Papers in Applied Geography*, *2*(4), 365–382. [CrossRef]

Hassan, M., Park, J.-H., & Han, M.-H. (2023). Enhancing livestock management with IoT-based wireless sensor networks: A comprehensive approach for health monitoring, location tracking, behavior analysis, and environmental optimization. *Journal of Sustainable Urban Futures*, *13*(6), 34–46.

Heins, B., Pereira, G. M., & Sharpe, K. (2023). Precision technologies to improve dairy grazing systems. *JDS communications*, *4*(4), 318–323. [CrossRef]

Hemme, T., Deeken, E., & Ramanovich, M. (2008). *IFCN dairy report. International farm comparison network* (pp. 25–29). IFCN Dairy Research Center.

Henchion, M. M., Regan, Á., Beecher, M., & MackenWalsh, Á. (2022). Developing 'smart' dairy farming responsive to farmers and consumer-citizens: A review. *Animals*, *12*(3), 360. [CrossRef] [PubMed]

Herlin, A., Brunberg, E., Hultgren, J., Högberg, N., Rydberg, A., & Skarin, A. (2021). Animal welfare implications of digital tools for monitoring and management of cattle and sheep on pasture. *Animals*, *11*(3), 829. [CrossRef]

Hnatiuc, M., & Caracostea, M. (2017). Automatic Calf Feeder System. *International Journal of Modeling and Optimization*, *7*(4), 218. [CrossRef]

Hofmann, W. (2024). Automating dairy farm grazing records using GPS technology. *Journal of New Zealand Grasslands*, *86*, 253–261. [CrossRef]

Horn, J., & Isselstein, J. (2022). How do we feed grazing livestock in the future? A case for knowledge-driven grazing systems. *Grass and Forage Science*, *77*(3), 153–166. [CrossRef]

Hossain, S., Jahan, M., & Khatun, F. (2022). Current status of dairy products in Bangladesh: A review on supply and utilization. *International Journal of Business, Management and Social Research*, *11*, 609–618.

Jensen, D. B., van der Voort, M., & Hogeveen, H. (2018). Dynamic forecasting of individual cow milk yield in automatic milking systems. *Journal of Dairy Science*, *101*(11), 10428–10439. [CrossRef] [PubMed]

Kaswan, S., Chandratre, G. A., Upadhyay, D., Sharma, A., Sreekala, S., Badgujar, P. C., Panda, P., & Ruchay, A. (2024). Applications of sensors in livestock management. In *Engineering applications in livestock production* (pp. 63–92). Elsevier.

Kaur, D., & Virk, A. K. (2024). Leveraging IoT for precision health monitoring in livestock with artificial intelligence. In *Data-driven farming* (pp. 1–18). Auerbach Publications.

Kazancoglu, Y., Ozbiltekin-Pala, M., Sezer, M. D., Kumar, A., & Luthra, S. (2022). Circular dairy supply chain management through Internet of Things-enabled technologies. *Environmental Science and Pollution Research*, 1–13. [CrossRef] [PubMed]

Kominami, H., & Lovell, S. T. (2012). An adaptive management approach to improve water quality at a model dairy farm in Vermont, USA. *Ecological Engineering*, *40*, 131–143. [CrossRef]

Kulish, T., Sokil, Y., Legeza, D., Sokil, O., Budnikevich, I., & Diyora, B. (2024). Digitalization of Consumers' Behavior Model in the Dairy Market. In *Data-centric business and applications: Modern trends in financial and innovation data processes 2023* (Vol. 1, pp. 187–205). Springer.

Kumar, R., Sinwar, D., Pandey, A., Tadele, T., Singh, V., & Raghuwanshi, G. (2022). IoT enabled technologies in smart farming and challenges for adoption. *Internet of Things and Analytics for Agriculture*, *3*, 141–164.

Lashari, M. H., Karim, S., Alhussein, M., Hoshu, A. A., Aurangzeb, K., & Anwar, M. S. (2023). Internet of Things-based sustainable environment management for large indoor facilities. *PeerJ Computer Science*, *9*, e1623. [CrossRef]

Lin, C.-F. (2019, May 10–11). *Blockchainizing food law: Implications for food safety, traceability, and sustainability* [Paper presentation]. Conference on Food Law and Policy: Food Safety and Technology Governance, Taipei, Taiwan.

Liu, N., Qi, J., An, X., & Wang, Y. (2023). A Review on Information Technologies Applicable to Precision Dairy Farming: Focus on Behavior, Health Monitoring, and the Precise Feeding of Dairy Cows. *Agriculture*, *13*(10), 1858. [CrossRef]

Mangla, S. K., Kazancoglu, Y., Ekinci, E., Liu, M., Özbiltekin, M., & Sezer, M. D. (2021). Using system dynamics to analyze the societal impacts of blockchain technology in milk supply chainsrefer. *Transportation Research Part E: Logistics and Transportation Review*, *149*, 102289. [CrossRef]

Mikhailichenko, S. M. (2023). Feeding system for cattle based on a wheeled robotic feeder. *Tractors and Agricultural Machinery*, *90*(1), 82–90. [CrossRef]

Minoofar, A., Gholami, A., Eslami, S., Hajizadeh, A., Gholami, A., Zandi, M., Ameri, M., & Kazem, H. A. (2023). Renewable energy system opportunities: A sustainable solution toward cleaner production and reducing carbon footprint of large-scale dairy farms. *Energy Conversion and Management*, *293*, 117554. [CrossRef]

Mottram, T. T. F., & den Uijl, I. (2022). Health and welfare monitoring of dairy cows. In *Digital agritechnology* (pp. 113–142). Elsevier.

Nasir, T. (2016). *Sustainable supply chain risk management in dairy industry: An empirical study in Bangladesh* [Ph.D. Thesis, Curtin University].

Niles, M. T., Wiltshire, S., Lombard, J., Branan, M., Vuolo, M., Chintala, R., & Tricarico, J. (2022). Manure management strategies are interconnected with complexity across US dairy farms. *PLoS ONE*, *17*(6), e0267731. [CrossRef]

Nleya, S. M., & Ndlovu, S. (2021). Smart dairy farming overview: Innovation, algorithms and challenges. In *Smart agriculture automation using advanced technologies: Data analytics and machine learning, cloud architecture, automation and IoT* (pp. 35–59). Springer.

Pandey, P., Pandey, A., Yan, L., Wang, D., Pandey, V., Meikap, B. C., Huo, J., Zhang, R., & Pandey, P. K. (2021). Dairy waste and potential of small-scale biogas digester for rural energy in India. *Applied Sciences*, *11*(22), 10671. [CrossRef]

Piwczyński, D., Gondek, J., Sitkowska, B., & Kolenda, M. (2020). Comparison of results coming from automatic milking system in selected countries in Europe and US. *Journal of Central European Agriculture*, *21*(2), 187–196. [CrossRef]

Quddus, A. (2018). Smallholder dairy farming in Bangladesh: A socioeconomic analysis. *Bangladesh Journal of Agricultural Economics*, *37*(1–2). Available online: https://ideas.repec.org/a/ags/bdbjaf/278754.html (accessed on 29 December 2024).

Rahman, M. M., Kabir, S. L., Khatun, M. M., Rahman, M. H., & Ansari, N. P. (2014). Past, present and future driving force in the enforcement and management of food safety law in Bangladesh. *Health, Safety and Environment*, *2*(4), 103–122.

Ramos, R. N. M. (2021). Family labour organization for dairy farming in western Mexico. Between the search for productivity and wellbeing. *Journal of Rural Studies*, *88*, 354–367. [CrossRef]

Saha, C. K., Nandi, R., Rahman, M. A., Alam, M. M., & Møller, H. B. (2024). Biogas technology in commercial poultry and dairy farms of Bangladesh: Present scenario and future prospect. *Biomass Conversion and Biorefinery*, *14*(7), 8407–8418. [CrossRef]

Samad, M. (2020). A six-decade review: Research on cattle production, management and dairy products in Bangladesh. *Journal of Veterinary Medical and One Health Research*, *2*(2), 183–404.

Saqib, Z. A., & Qin, L. (2024). Investigating effects of digital innovations on sustainable operations of logistics: An empirical study. *Sustainability*, *16*(13), 5518. [CrossRef]

Saqib, Z. A., Qin, L., Menhas, R., & Lei, G. (2023). Strategic Sustainability and Operational Initiatives in Small-and Medium-Sized Manufacturers: An Empirical Analysis. *Sustainability*, *15*(7), 6330. [CrossRef]

Saqib, Z. A., & Zhang, Q. (2021). Impact of sustainable practices on sustainable performance: The moderating role of supply chain visibility. *Journal of Manufacturing Technology Management*, *32*(7), 1421–1443. [CrossRef]

Shamsuddoha, M. (2005). Poultry rearing-an alternative income generating activity for rural women development of Bangladesh. *Chittagong University Journal of Commerce*, *19*.

Shamsuddoha, M. (2009). Development of livestock sector through leading NGO in Bangladesh. *The USV Annals of Econom-ics and Public Administration*, *9*(1), 36–44.

Shamsuddoha, M., Nasir, T., & Hossain, N. U. I. (2023a). A sustainable supply chain framework for dairy farming opera-tions: A system dynamics approach. *Sustainability*, *15*(10), 8417. [CrossRef]

Shamsuddoha, M., Nasir, T., & Ibne Hossain, N. U. (2023b). *Integrating circular economy and reverse logistics for achieving sustainable dairy operations data analytics for supply chain networks* (pp. 211–226). Springer.

Shamsuddoha, M., Koul, S., & Taylor, I. W. (2024). Eco-efficient dairy waste treatment: Validating a sustainable system dynamics framework. *Operations Research Forum*, *5*(1), 12. [CrossRef]

Shingh, S., Kamalvanshi, V., Ghimire, S., & Basyal, S. (2020). Dairy supply chain system based on blockchain technology. *Asian Journal of Economics, Business and Accounting*, *14*(2), 13–19. [CrossRef]

Shortall, O., Sutherland, L. A., Ruston, A., & Kaler, J. (2018). True cowmen and commercial farmers: Exploring vets' and dairy farmers' contrasting views of 'good farming'in relation to biosecurity. *Sociologia Ruralis*, *58*(3), 583–603. [CrossRef]

Simões Filho, L. M., Lopes, M. A., Brito, S. C., Rossi, G., Conti, L., & Barbari, M. (2020). Robotic milking of dairy cows: A review. *Semina: Ciências Agrárias*, *41*(6), 2833–2850. [CrossRef]

Sodhi, S. S., Singh, J., Kashyap, N., Kansal, S., & Verma, H. (2017). Perception of member dairy farmers about animal health care services and input facilities provided by milkfed. *Journal of Animal Research*, *7*(5), 957–963.

Solankı, A., & Pal, Y. (2021). A comprehensive review to study and implement solar energy in dairy industries. *Journal of Thermal Engineering*, *7*(5), 1216–1238. [CrossRef]

Sukhoveeva, O. (2021). Carbon calculators as a tool for assessing greenhouse gas emissions from livestock. *Doklady Earth Sciences*, *497*(1), 266–271. [CrossRef]

Tangorra, F. M., Buoio, E., Calcante, A., Bassi, A., & Costa, A. (2024). Internet of Things (IoT): Sensors Application in Dairy Cattle Farming. *Animals*, *14*(21), 3071. [CrossRef] [PubMed]

Trevarthen, A., & Michael, K. (2007, July 9–11). *Beyond mere compliance of RFID regulations by the farming community: A case study of the Cochrane dairy farm* [Paper presentation]. International Conference on the Management of Mobile Business (ICMB 2007), Toronto, ON, Canada.

Tzanidakis, C., Tzamaloukas, O., Simitzis, P., & Panagakis, P. (2023). Precision livestock farming applications (PLF) for grazing animals. *Agriculture*, *13*(2), 288. [CrossRef]

Uddin, M., Hemme, T., Ndambi, O., & Khan, M. (2017). Impact of dairy support services and strategies on reduction of cost of milk production in different dairy production systems in Bangladesh: Implications for rural livelihood improvement. *Asian Journal For Poverty Studies (AJPS)*, *3*(2), 96–104.

Van der Leek, M. L. (2015). Beyond traditional dairy veterinary services: 'It's not just about the cows!'. *Journal of the South African Veterinary Association*, *86*(1), 1–10. [CrossRef] [PubMed]

van Erp-van der, E., & Rutter, S. M. (2020). Using precision farming to improve animal welfare. *CABI Reviews*, *15*(51), 1–10. [CrossRef]

Verdon, M., Langworthy, A., & Rawnsley, R. (2021). Virtual fencing technology to intensively graze lactating dairy cattle. II: Effects on cow welfare and behavior. *Journal of Dairy Science*, *104*(6), 7084–7094. [CrossRef]

Wiggans, G. R., Cole, J. B., Hubbard, S. M., & Sonstegard, T. S. (2017). Genomic selection in dairy cattle: The USDA experience. *Annual Review of Animal Biosciences*, *5*(1), 309–327. [CrossRef] [PubMed]

Wijers, G. D. (2019). Inequality regimes in Indonesian dairy cooperatives: Understanding institutional barriers to gender equality. *Agriculture and Human Values*, *36*(2), 167–181. [CrossRef]

Yoo, H.-S., & Kim, S.-W. (2014). Virtual farmers training: Realistic simulation with amusements using historic simulation and game storyline. *International Journal of Multimedia and Ubiquitous Engineering*, *9*, 121–130. [CrossRef]

Zainab, M. K., Arumugam, N., & Bonaventure, B. (2016). The sustainability practices among dairy farmers: The case of Johor. *International Journal of Agricultural Management and Development (IJAMAD)*, *6*(1), 109–115.