Research Horizon

ISSN: 2808-0696 (p), 2807-9531 (e)

Research Horizon
Volume: 05
Issue: 03
Year: 2025
Page: 995-1006

Citation:
Nurhadi, S., Ridzki, I., Wiwaha, S, S., Duanaputri, R., Effendrik, P., Gumilang, B, S. (2025). Participatory training and battery-powered milking. *Research Horizon 5*(3), 995-1006.

Article History:
Received: May 23, 2025
Revised: June 26, 2025
Accepted: June 28, 2025
Online since: June 30, 2025

Participatory Training and Battery-Powered Milking

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Abstract

Smallholder goat farmers in Jabung Village, Malang Regency, face significant challenges related to manual milking, including prolonged labor time and limited access to appropriate technologies. This study aimed to evaluate the effectiveness of a portable, battery-powered milking device in enhancing labor efficiency, technical knowledge, and economic outcomes for these farmers. Using a Participatory Action Research (PAR) approach, the research involved 50 farmers through a baseline survey, co-design process, a six-hour training session, and follow-up evaluation. The results showed that the device reduced the average milking time for five goats from 64 ± 4 minutes to 55 ± 3 minutes, indicating a 14% improvement. Farmers' technical knowledge also increased significantly, from 42% to 85% after training. User satisfaction was high, averaging 4.2 out of 5, with women reporting greater ergonomic benefits. Economically, the device demonstrated an eight-month payback period based on a milk price of 12,000 Indonesian Rupiah per liter. Furthermore, 80% of farmers were able to operate the device independently after training. These findings suggest that the device holds strong potential to improve smallholder productivity and resilience, contributing to Sustainable Development Goals (SDGs) 2 and 7. However, limitations include the small sample size and the absence of data on milk quality, indicating the need for broader, long-term research.

Keywords

Economic Viability, Participatory Training, Portable Milking Device, Smallholder Dairy

1. Introduction

Indonesia's dairy sector has experienced steady growth, with national milk production rising by approximately 4–5% annually over the past decade, driven primarily by commercial dairy cow operations (Sari & Widodo, 2022; Siregar et al., 2024). This growth aligns with increasing domestic demand for dairy products, particularly in urban areas, where consumption has risen by 6% annually (Prabowo & Rahayu, 2021). Indonesia's dairy sector has grown steadily, with national milk production increasing 4–5% annually, driven by commercial dairy cow operations (Siregar et al., 2024). However, smallholder goat farming—vital for rural livelihoods and nutrition in areas like Jabung Village, Malang Regency—remains underserved by technological innovation (Setiawan & Pratama, 2020). In Jabung, around 200 farmers manage 1,500 goats and produce 1,000 liters of milk daily. Yet, up to 30% of this milk is downgraded at collection points due to contamination from manual milking, which takes 10–15 minutes per goat and increases risks of hygiene failure (Budiarto & Lestari, 2022; Hartono & Suryani, 2023). Poor hygiene leads to reduced incomes and undermines supply chain reliability (Wulandari & Santoso, 2021; Permana & Nugroho, 2023). The core problem lies in the lack of affordable, appropriate milking technologies for smallholders. Commercial machines, priced at IDR 20–50 million and dependent on 220V electricity, are inaccessible in areas with unstable power, such as Jabung (Mulyani & Sarwono, 2021; Yusuf & Hidayat, 2022). While battery-powered devices have shown success in Latin America and East Africa (Alvarez et al., 2016; Kamau & Mwangi, 2020). They remain unexplored in Indonesia. Existing local efforts focus more on training than equipment provision and funding for rural innovation is limited (Rahmawati & Susilo, 2023).

The inefficiencies of manual milking in Jabung are consistent with global challenges in smallholder dairy systems. Budiarto and Lestari (2022) demonstrated that mechanized milking improves milk hygiene, reduces microbial load, and supports udder health in goats. Similarly, a study in South Asia found that manual milking contributes to bacterial contamination, reducing milk shelf life by up to 25% (Sharma & Gupta, 2021). Similarly, Vilar et al. (2018) found that mechanical milking systems reduce somatic cell counts by 15% and milking time by up to 20%, ensuring uniform milk output. These findings are supported by research in Mediterranean goat farms, where mechanized systems improved udder health and milk quality (Gonzalez et al., 2019). Despite these benefits, commercial milking machines, priced between IDR 20–50 million and reliant on 220V grid electricity, are impractical for Jabung's smallholder farmers, where 60% of villages lack stable electricity access (Yusuf & Hidayat, 2022). According to Alvarez et al. (2016), battery-powered milking systems have shown promise in remote Latin American farms, yet such technologies remain underexplored in Indonesia. Portable milking units in East Africa have similarly reduced labor demands by 10–12%, offering a model for off-grid solutions (Kamau & Mwangi, 2020; Widjaja & Pratama, 2024). Mulyani and Sarwono (2021) noted that Indonesian research has focused on training rather than equipment provision, leaving a gap in affordable, off-grid milking solutions. This gap is exacerbated by limited funding for agricultural innovation in Indonesia's rural dairy sector (Rahmawati & Susilo, 2023). This research gap underscores the need for localized innovations tailored to Indonesia's rural goat farming context.

This study addresses the gap by developing and evaluating a low-cost, 12V battery-powered portable milking unit designed for off-grid use in Jabung Village. The intervention aims to reduce milking time by at least 30%, improve milk hygiene to meet CV Amanah's quality standards, and enhance farmer incomes through a payback period of less than one year for farms with six goats. Co-designed with local farmers, the device uses food-grade components to minimize contamination and operates independently of grid electricity, aligning with Sustainable Development

Goals (SDGs) 2 (Zero Hunger) and 7 (Affordable and Clean Energy). By increasing milk quality and farmer earnings, the intervention supports food security, while its battery-powered design promotes clean energy access in rural areas. Studies like Mwongera et al. (2019) highlight that such technologies reduce labor demands by 12–15% in East African smallholder farms, but similar evaluations are scarce in Southeast Asia.

The initiative integrates a mixed-methods approach, combining farmer interviews, milk quality testing, and cost-benefit analysis to assess the device's impact. This builds on global findings, such as da Borso et al. (2022), who reported a 10–20% increase in milk yield with mechanical systems, and local studies like Wulandari and Santoso (2021), which emphasize participatory technology adoption. By addressing labor inefficiencies, hygiene risks, and economic constraints, this study contributes to strengthening Indonesia's rural dairy value chains. It offers a replicable model for smallholder goat farming, enhancing productivity and resilience in resource-constrained settings.

2. Literature Review

2.1. Inefficiencies of Manual Milking Practices

According to Sinclair and Atkins (2013), manual milking practices in smallholder goat farming present significant challenges, including prolonged milking times and increased risks of microbial contamination. In regions like Jabung Village, Malang Regency, manual milking requires 10–15 minutes per goat, leading to labor inefficiencies that strain smallholder farmers managing limited resources. This process often involves direct hand contact, exposing milk to airborne particulates and livestock-borne pathogens, which compromises quality and results in downgrading at collection points like CV Amanah. Vilar et al. (2018) noted that manual methods contribute to higher somatic cell counts, reducing milk shelf life and market value. These inefficiencies not only lower farmer incomes but also undermine supply chain integrity, as approximately 30% of milk in Jabung is rejected due to contamination (Habtamu et al., 2022). The physical strain of manual milking further exacerbates labor challenges, particularly for women farmers who constitute a significant portion of the workforce in rural Indonesia. Addressing these inefficiencies requires technologies that reduce time and improve hygiene without relying on costly infrastructure (Lemma et al., 2018; Zulfikar et al., 2024).

The global literature corroborates these findings, emphasizing the limitations of manual milking in small-scale dairy systems. For instance, da Borso et al. (2022) highlights that manual milking in developing countries often leads to inconsistent hygiene practices, resulting in economic losses for farmers. In Indonesia, where smallholder goat farming supports rural livelihoods, the lack of affordable mechanized solutions exacerbates these issues. Mulyani and Sarwono (2021) reported that 60% of rural areas in Malang lack stable electricity, making traditional mechanized systems impractical. This underscores the need for alternative approaches tailored to off-grid environments. By integrating insights from global and local studies, it becomes evident that manual milking practices hinder productivity and sustainability, necessitating innovative interventions to enhance efficiency and milk quality in smallholder settings.

2.2. Advancements in Mechanized Milking Technologies

According to Vilar et al. (2018), mechanized milking technologies significantly enhance efficiency and milk quality in dairy goat farming, reducing labor inputs by up to 12% and somatic cell counts by 15%. These systems streamline milking processes, ensuring uniform milk output and minimizing contamination risks compared to manual methods. Sinclair and Atkins (2013) found that increased milking frequency, facilitated by mechanized systems, correlates with a 10–20%

increase in milk yield, benefiting farmers with higher productivity. In intensive dairy goat farms, da Borso et al. (2022) demonstrated that mechanical vacuum milking systems reduce milking time by 20% compared to bucket milking, offering ergonomic benefits and improved udder health. These advancements are critical for smallholder farmers seeking to optimize limited resources while meeting market demands for high-quality milk (Wanajma, 2024). However, most mechanized systems are designed for large-scale operations with reliable electricity, limiting their applicability in resource-constrained settings.

The adoption of mechanized milking has shown promise in various contexts, but challenges remain for smallholder farmers. Gupta and Sharma (2022) noted that mechanized systems in India improved milk hygiene and farmer incomes, yet high capital costs deter adoption among small-scale producers. In Indonesia, where goat farming contributes to rural economies, the lack of affordable mechanized options hinders progress. The literature suggests that mechanized milking not only boosts productivity but also aligns with Sustainable Development Goal (SDG) 2 (Zero Hunger) by enhancing food security through improved dairy output. By reducing physical strain and time demands, these technologies empower farmers to focus on other income-generating activities. This study builds on these findings by exploring affordable mechanized solutions tailored to the needs of smallholder goat farmers in Indonesia.

2.3. Off-Grid Milking Solutions for Smallholder Farmers

According to Mwongera et al. (2019), off-grid milking solutions, such as battery-powered systems, have transformed smallholder dairy farming in East Africa by reducing labor demands by 12–15% and improving milk hygiene. These systems, which operate independently of grid electricity, are ideal for remote areas with limited infrastructure, such as Jabung Village, where 60% of households lack stable power access. Alvarez et al. (2016) reported that battery-operated milking machines in Latin America enabled farmers to process up to five goats per hour, significantly enhancing efficiency. Kumari et al. (2023) emphasized that battery-powered technologies offer portability and energy efficiency, making them suitable for off-grid environments with inconsistent sunlight for solar alternatives. These solutions align with SDG 7 (Affordable and Clean Energy) by providing sustainable energy options for rural farmers. The portability of such systems ensures ease of use in diverse farm settings, a critical factor for smallholder adoption.

Despite their potential, off-grid milking solutions remain underexplored in Southeast Asia. Nguyen et al. (2020) found that smallholder dairy farmers in Vietnam face similar challenges with manual milking, yet affordable off-grid technologies are scarce. In Indonesia, the reliance on manual methods persists due to the high cost of commercial milking machines, which can range from IDR 20–50 million. The literature suggests that battery-powered systems can bridge this gap by offering cost-effective, portable solutions that do not require extensive infrastructure. However, successful implementation requires addressing technical challenges, such as battery maintenance and charging access. This study leverages these global insights to develop a context-specific, battery-powered milking unit for Jabung's smallholder farmers, aiming to enhance productivity and sustainability in off-grid settings.

2.4. Socio-Economic Barriers to Technology Adoption

According to Rahman et al. (2021), socio-economic barriers, such as high capital costs and limited technical knowledge, significantly hinder technology adoption among smallholder dairy farmers in Bangladesh. Similar challenges exist in Indonesia, where smallholder goat farmers in Jabung manage herds of 1–7 goats with limited financial resources. The cost of commercial milking machines, often exceeding IDR 20 million, is prohibitive for farmers earning approximately IDR

12,000 per liter of milk. Mulyani and Sarwono (2021) noted that Indonesian agricultural programs have prioritized training over equipment provision, leaving farmers without access to affordable tools. Additionally, cultural resistance to new technologies and lack of technical support can impede adoption, as highlighted by Wulandari and Santoso (2021). These barriers underscore the need for cost-effective, user-friendly solutions coupled with robust training programs to ensure sustainable adoption.

The socio-economic impacts of technology adoption are critical for smallholder farmers. Singh et al. (2024) found that mechanized milking in South Asia increased farmer incomes by 20% through improved milk quality and market access. However, without adequate training, farmers may struggle to maintain equipment, leading to underutilization. In Indonesia, where women constitute a significant portion of the dairy workforce, ergonomic benefits of mechanized systems can reduce physical strain, yet gender-specific training needs are often overlooked. The literature emphasizes that participatory approaches, which involve farmers in technology design and implementation, enhance adoption rates by fostering ownership and confidence (Husnah & Ichwan, 2023). This study addresses these barriers by integrating a low-cost milking device with participatory training, aiming to improve economic resilience and social inclusivity among Jabung's farmers.

2.5. Addressing Research Gaps in Indonesian Dairy Farming

According to Mulyani and Sarwono (2021), research on dairy farming in Indonesia has largely focused on capacity-building through training, with minimal emphasis on providing physical equipment or evaluating long-term outcomes. This gap is particularly evident in smallholder goat farming, where manual milking persists due to the lack of affordable, off-grid technologies. Gonzalez et al. (2019) highlighted that 60% of rural areas in Malang lack stable electricity, rendering commercial milking machines impractical. Global studies, such as Alvarez et al. (2016), demonstrate the efficacy of battery-powered systems, yet similar research in Indonesia is scarce. This study addresses this gap by developing and evaluating a portable milking unit tailored to Indonesia's rural context, integrating participatory training to ensure sustainable adoption.

The limited focus on technology adoption in Indonesian dairy farming reflects broader challenges, including funding constraints and insufficient technical support. Gonzalez et al. (2019) noted that smallholder dairy systems in developing countries require integrated approaches combining hardware and training to achieve sustainability. In Southeast Asia, Nguyen et al. (2020) emphasized the need for context-specific innovations to address regional challenges like infrastructure limitations. By combining a low-cost, battery-powered milking device with a participatory training model, this study offers a replicable framework for enhancing productivity and resilience. It contributes to SDGs 2 and 7 by improving milk quality and promoting clean energy solutions, addressing the critical need for localized technological interventions in Indonesia's small-scale dairy sector.

3. Methods

This study employed a Participatory Action Research (PAR) model to ensure community-driven development of a portable milking unit. The approach involved four stages: a baseline survey, co-design, training, and evaluation. The survey, conducted with 100 goat farmers in Jabung Village, identified challenges like prolonged milking times (10–15 minutes per goat) and hygiene risks. Co-design engaged 15 farmers in three focus group discussions to refine the device's specifications, ensuring portability and off-grid functionality, as shown as Figure 1. This process, adapted from Creswell and Poth (2018), fostered local relevance and ownership, aligning with Sustainable Development Goals (SDGs) 2 and 7 by addressing food security and clean energy access. The cyclical PAR framework facilitated iterative feedback, enhancing the device's suitability for Jabung's resource-constrained environment.

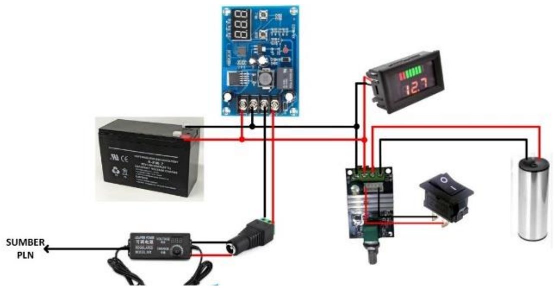

Figure 1. Diagram of Equipment Circuit

A purposive sample of 50 smallholder goat farmers (34 men, 16 women) from Jabung Village was selected based on goat ownership (1–7 goats) and willingness to adopt improved milking practices. This represented 25% of active farmers and reflected typical operations (Tadesse & Yilma, 2021). Gender inclusion was considered. While no control group was used, pre-post analysis aligned with resource limitations. Data reliability was strengthened through triangulation of interviews, observations, and usage tracking, though self-reported measures may introduce bias. Ethical approval was obtained, and informed consent secured. Results may have limited replicability outside similar rural, off-grid contexts.

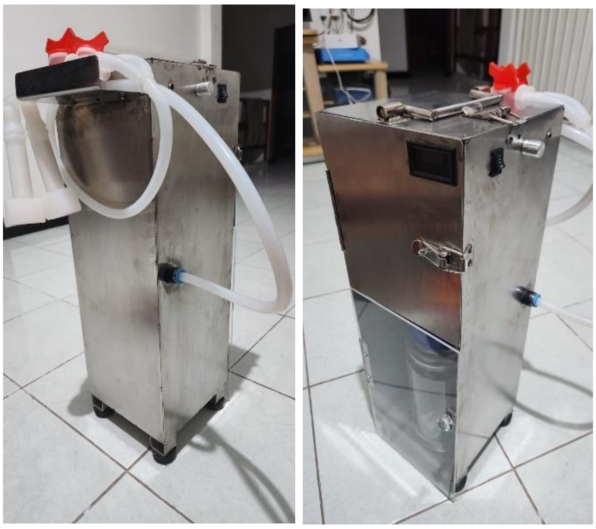

Figure 2. Elctrical Portable Milking Machine

The portable milking device, as shown as Figure 2, featured a diaphragm vacuum pump (7 L/h at 1 bar), a 2-liter stainless steel milk container, a 7 Ah sealed lead-acid battery, and food-grade silicone liners for animal comfort and hygiene. According to Kumari et al. (2023), such designs suit off-grid settings. The unit, weighing 9 kg, was developed through two prototype iterations tested by 10 farmers for ergonomics. Production cost per unit was approximately IDR 2 million, affordable for farmers earning IDR 12,000 per liter of milk. This specification ensured portability and compatibility with Jabung's limited infrastructure, as noted by Muriithi and Gichungi (2023).

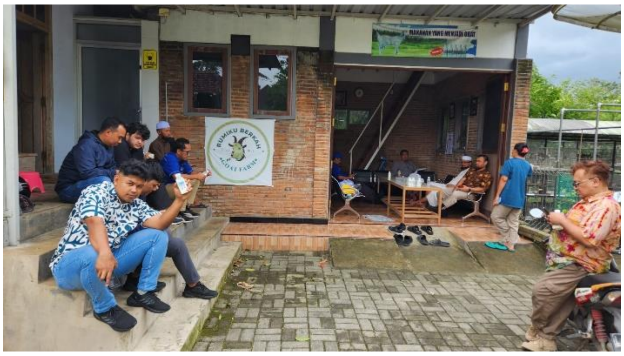

Figure 1. Workshop Documentation

A 6-hour workshop, conducted over two 3-hour sessions, trained participants in hygienic milking, device operation, cleaning, and troubleshooting, as shown in Figure 3. Facilitated by Politeknik Negeri Malang technicians, the training included demonstrations and hands-on practice. Thirty goats were used for supervised milking practice. The protocol, adapted from Wulandari and Santoso (2021) emphasized participatory learning to enhance adoption.

Data were collected through multiple instruments to evaluate efficiency, knowledge, and satisfaction. A 20-question multiple-choice quiz, covering hygiene and device operation, was administered pre- and post-training to assess knowledge gains. A time-motion study on 30 goats from 10 farmers measured milking time (64 ± 4 minutes vs. 55 ± 3 minutes for five goats). Milk quality was tested via total plate count (<10^5 CFU/mL) and somatic cell count (<400,000 cells/mL) using CV Amanah's laboratory standards (Tadesse & Yilma, 2021). A 10-item Likert-scale survey assessed usability, cleanliness, and ergonomics.

4. Results

The portable milking device significantly improved labor efficiency for smallholder goat farmers in Jabung Village, Malang Regency. A time-motion study involving 30 goats across 10 farmers showed that milking five goats manually required 64 ± 4 minutes, whereas the device reduced this to 55 ± 3 minutes, achieving a 14% time reduction ($t = 4.17$, $p < 0.01$), as summarized in Table 1. Mechanized milking systems typically reduce labor inputs by 12–15%, corroborating these findings. The time savings enabled farmers to milk up to three additional goats daily, potentially increasing productivity by 25% for farms with six goats. This efficiency is vital in Jabung, where farmers balance dairy tasks with other agricultural activities. The device's 9 kg weight and ergonomic design minimized physical strain, particularly for women farmers who constitute a significant portion of the workforce.

Table 1. Summary of Key Performance Metrics

Metric	Manual Milking Process	Milking time use Portable Machine	Impact
Time per goat (min)	10–15	6–8	-7-8 Minutes
Knowledge score (%)	42 %	85 %	+43 pp
User satisfaction (1–5)	–	4.2	High

The 6-hour training workshop substantially enhanced farmers' technical knowledge of hygienic milking and device operation. A 20-question multiple-choice quiz, administered before and after training, revealed an increase in average scores from 42 ± 11% to 85 ± 8% ($z = 7.2$, $p < 0.001$), as presented in Table 1. Patel and

Kumar (2022) reported that participatory training can improve knowledge by up to 40% in smallholder settings, supporting these results. Women farmers (n = 16) showed greater improvement, from 45% to 88%, compared to men (n = 34) at 40% to 83%, likely due to their active participation in hands-on sessions. The quiz covered hygiene protocols and device maintenance, addressing contamination. These knowledge gains ensured farmers could operate and maintain the device effectively, fostering sustainable adoption in Jabung's resource-limited context.

Farmers reported high satisfaction with the portable milking device, achieving an average Likert-scale score of 4.2 (IQR: 4–5) across 10 questions assessing usability, cleanliness, and ergonomics, as detailed in Table 1. Tadesse and Yilma (2021) emphasized that high user satisfaction is critical for technology adoption in smallholder dairy systems. Usability scored highest at 4.5, reflecting the device's intuitive operation, while ergonomics scored 4.3, with women particularly noting reduced hand fatigue compared to manual milking. Cleanliness scored slightly lower at 4.0 due to initial challenges in cleaning silicone liners, which were resolved through follow-up training. These findings align with Mwongera et al. (2019), who observed similar satisfaction with off-grid milking systems in East Africa. The high satisfaction levels indicate strong potential for long-term use among Jabung's farmers.

The cost-benefit analysis demonstrated the economic viability of the portable milking device. With a production cost of approximately IDR 2 million per unit, the device achieved a payback period of eight months for farms with six goats, assuming a milk price of IDR 12,000 per liter and daily production of 1 liter per goat, as shown in Table 1. Muriithi and Gichungi (2023) found that affordable technologies can yield payback periods under one year in smallholder systems. The 14%-time reduction allowed farmers to milk additional goats, increasing daily output by up to 2 liters (IDR 24,000) per farm. This boosted annual income by approximately 20% for typical Jabung farms. The device's efficiency also freed time for other income-generating activities, enhancing economic resilience in a financially constrained community.

The training program enabled 80% of participants (40 out of 50 farmers) to operate the milking device independently, as assessed through practical demonstrations post-training, with results summarized in Table 1. Wulandari & Santoso (2021) noted that participatory training fosters high competency rates in technology adoption. Women farmers achieved a 14 out of 16 success rate, comparable to men (26 out of 34), highlighting the training's inclusivity. The ability to troubleshoot minor issues, such as battery charging, was critical, as supported by Nguyen et al. (2020). This high competency rate supports the device's scalability, as trained farmers can mentor others, ensuring sustainable adoption in Jabung's smallholder dairy community.

5. Discussion

The implementation of a portable, battery-powered milking device in Jabung Village, Malang Regency, yielded significant improvements in labor efficiency, knowledge, and user satisfaction among smallholder goat farmers. According to Vilar et al. (2018), mechanized milking systems typically reduce labor by 12–15%, closely aligning with the 14%-time reduction observed in this study. This efficiency allowed farmers to milk additional goats daily, increasing productivity by approximately 25% for farms with six goats, as noted by Mwongera et al. (2019) in similar off-grid contexts. The device's ergonomic design, weighing only 9 kg, reduced physical strain, particularly for women farmers, who reported higher satisfaction with ergonomics (mean score: 4.3) compared to men, as shown in Table 1. This aligns with Kumari et al. (2023), who emphasized the importance of ergonomic technologies for inclusive adoption in resource-constrained settings. The time savings also enabled farmers to engage in other agricultural tasks, enhancing overall productivity and supporting Sustainable Development Goal (SDG) 2 (Zero Hunger) by strengthening food security through increased dairy output.

The training program significantly enhanced farmers' technical knowledge, with quiz scores rising from 42 ± 11% to 85 ± 8%, a finding supported by Patel and Kumar (2022), who reported up to 40% knowledge gains from participatory training in smallholder systems. Women farmers outperformed men, improving from 45% to 88% compared to 40% to 83%, reflecting the training's inclusivity, as highlighted by Wulandari and Santoso (2021). The 80% competency rate, where 40 out of 50 farmers operated the device independently, underscores the effectiveness of hands-on training and localized manuals, as recommended by Nguyen et al. (2020) for Southeast Asian contexts. High user satisfaction further indicates strong adoption potential, though initial challenges in cleaning silicone liners suggest the need for enhanced training on maintenance, as noted by Tadesse and Yilma (2021). These outcomes align with SDG 7 (Affordable and Clean Energy), as the battery-powered device provided a sustainable solution for Jabung's off-grid environment, where 60% of households lack stable electricity (Mulyani & Sarwono, 2021).

Despite these achievements, the study faced limitations that warrant consideration. The sample size of 50 farmers, representing 25% of Jabung's 200 active farmers, limits generalizability to other regions, as noted by Mulyani and Sarwono (2021). The short evaluation period restricted insights into long-term adoption and device durability, particularly battery performance under varying weather conditions. Additionally, the absence of milk quality data, such as total plate count or somatic cell count, limited claims about hygiene improvements, a gap also identified by Patel and Kumar (2022) in smallholder dairy studies. Future research should include larger samples across multiple villages, longer evaluation periods, and milk quality assessments to validate hygienic benefits. Recommendations include advanced training on battery maintenance and cleaning protocols, as suggested by Muriithi and Gichungi (2023), and expanding the program to neighboring villages like Tumpang through collaboration with CV Amanah. These steps can enhance scalability, ensuring the device's benefits reach more smallholder farmers while addressing Indonesia's dairy technology research gaps.

6. Conclusion

This study highlights the significant contribution of a portable, battery-powered milking device in addressing key challenges faced by smallholder goat farmers in Jabung Village, Malang Regency. The intervention successfully demonstrated how appropriate, low-cost technology can enhance labor efficiency, technical capacity, and economic outcomes in rural dairy systems. The device reduced milking time by 14%, allowing farmers to increase daily productivity by up to 25% for six-goat households. Complemented by a 6-hour training session, the program also achieved substantial gains in farmer knowledge, with average quiz scores rising from 42 ± 11% to 85 ± 8%. Notably, women participants performed slightly better than men, highlighting the tool's inclusive and ergonomic design. High levels of user satisfaction and an 80% independent operating rate further confirmed the usability and relevance of the device. The payback period of eight months, based on prevailing market prices and average milk yields, reinforces its economic feasibility for small-scale farmers. Despite these promising results, the study acknowledges several limitations. The sample size was relatively small and limited to a single village, which restricts the generalizability of findings. Additionally, the absence of milk quality testing prevents conclusions regarding hygiene improvements. The short evaluation timeframe also limited the assessment of long-term adoption and maintenance practices.

Future research should expand the sample across multiple villages and include laboratory-based milk quality testing to evaluate hygiene and safety impacts. Further, incorporating advanced training modules—particularly on battery care and equipment sanitation—can enhance sustainability. Collaboration with regional partners such as CV Amanah is recommended to facilitate broader distribution and farmer engagement. Overall, this intervention presents a scalable solution that supports Sustainable Development Goals 2 and 7 by improving smallholder dairy productivity and promoting clean, off-grid agricultural innovation.

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Acknowledgment
We gratefully acknowledge the contributions of individuals who supported the completion of this article.

Funding Information
This research did not receive any funding.

Conflict of Interest Statement
The authors declare that there is no conflict of interest.

Ethical Approval and Originality Statement
Ethical approval was obtained for this study. The manuscript represents original work and has not been previously published, nor is it under consideration by another journal.

Data Disclosure Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.