ADMI JUIT Jurnal Ilmiah Teknik
OPEN ACCESS
JUIT Vol 5 No. 1 | January 2026 | ISSN: 2828-6936 (Print), ISSN: 2828-6901 (online), Page. 29-46

Closed Loop: Integrated Water, Nutrient, and Energy Recovery Systems for Sustainable Dairy Production (Case: Dairy Farming)

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Article History
Received : December 07, 2025
Accepted : December 23, 2025
Published : December 24, 2025
Available Online:
December 24, 2025

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Cite This Article:
Stephanus Benedictus Bera Liwun. (2025). Closed Loop: Integrated Water, Nutrient, and Energy Recovery Systems for Sustainable Dairy Production (Case: Dairy Farming). Jurnal Ilmiah Teknik, 5(1), 29–46.

DOI:
https://doi.org/10.56127/juit.v

Abstract: The dairy industry is very important to the economy, but it has big problems with sustainability since it doesn't use resources well and doesn't handle waste well. Eco-Efficiency (13.1%) and Technical Efficiency (58.7%) are still very low in Serbia because of ongoing structural inefficiencies. In Indonesia, where 90% of dairy farms are operated by smallholders, an estimated 84% of manure is discharged untreated, contributing to greenhouse gas emissions and eutrophication. To solve these problems, we need to use Circular Economy ideas, such as closed-loop nutrient, energy, and water flows and integrated resource recovery. This review evaluates opportunities, sustainability gains, and barriers to implementing closed-loop systems across the dairy supply chain. The objectives include assessing farm-level efficiency, quantifying environmental and economic benefits of manure-derived resource recovery, evaluating circular feed substitution, and analysing biogas adoption barriers among smallholders. The research integrates findings from Stochastic Frontier Analysis, Life Cycle Assessment and Costing, Multi-regional Input–Output analysis, membrane-based water reuse models, and system dynamics, complemented by qualitative surveys of Indonesian farmers. Integrated recovery systems yielded carbon-negative results (up to –1790 kg CO_2 eq/year) and significant economic advantages ($825–$1,056/year). Biogas cut down on the consumption of LPG by about 45%. Circular feeds made more milk and had less of an effect, while treating whey membranes slashed the need for fresh water by 67–90%. Closed-loop solutions make dairy farming much more sustainable, but they need help from policymakers to be able to grow because of high investment costs and ongoing structural inefficiencies.

Keywords: Circular Economy, Eco-Efficiency, Resource Recovery

INTRODUCTION

The dairy industry farming industry is quite important for the economies of many countries and creates a lot of jobs (Latif *et al.*, 2023). But the high demand and heavy production have put a lot of stress on the environment and resources (Novaković *et al.*, 2025). Low resource efficiency and bad waste management are two big problems. In Indonesia, almost 90% of dairy farms are smallholder operations, and about 84% of dairy manure is thrown away without being processed, which pollutes the environment (Haryanto *et al.*, 2025).

The environmental effects are greenhouse gas (GHG) emissions and nutrient losses (Nitrogen and Phosphorus). Research in Serbia showed that the average Eco-Efficiency (EE) of dairy farms was quite low, at just 13.07%. Also, a study of efficiency using Technical Efficiency (TE) showed an average score of 58.70%. This means that input utilisation may be cut by 41.30% without changing output levels (Novaković *et al.*, 2025). Nitrogen losses in dairy systems in China are very high. Ammonia (NH3) emissions make up more than 60% of the total N loss in livestock production (Fang *et al.*, 2020; Ma *et al.*, 2021).

Because of these problems with sustainability, it is very important to use the Circular Economy (CE) method (Novaković *et al.*, 2025). CE's goals are to reduce waste and make the best use of resources through recycling, renewable energy, and optimising inputs (Latif *et al*., 2023; Mammi *et al.*, 2025). This method comprises using by-products from the agri-food industry as alternative feed (Mammi *et al.*, 2022) and turning livestock waste into energy (biogas) and nutrients that may be used again (Orner *et al.*, 2021).

RESEARCH METHOD

Materials and Tools

Circular feedstuffs come from adding agro-industrial by-products such Former Foodstuff Products (FFP) (waste from baking, like pasta, bread, and cookies) and Wheat Distiller's Grain with Solubles (WDGS). FFP has a lot of starch (41.33% DM) and is easy to digest (93.03% in 7 hours). Waste Biomass comes from the poop of dairy cows and the whey from buffalo and cows (which is a by-product of making cheese). This research is a articles review.

Anaerobic digestion (AD) is used to make biogas, membrane techniques like ultrafiltration (UF) and nanofiltration (NF) are used to get water back from whey, and gasification/pyrolysis of manure is used to make energy by-products like biochar.

Database and Search Strategy

The review combines results from studies that used different methods:

1. Efficiency Assessment: Stochastic Frontier Analysis (SFA) was used on Farm Accountancy Data Network (FADN) data to find Technical Efficiency (TE) and Eco-Efficiency (EE).

2. Environmental Impact and Cost Analysis: Life Cycle Assessment (LCA) is used to measure environmental effects including carbon footprint and eutrophication, while Life Cycle Cost Analysis (LCCA) is used to find Equivalent Uniform Annual Worth (EUAW).
3. System Modelling: We employed both qualitative (DPSIR) and quantitative (SFD/CLD) System Dynamics methods to model CE implementation strategies. In the case study of the Taruna Mukti Farmer Group, we got a deviation level (MAPE) of 16.3%.
4. Field Data: Panel data from dairy farming homes in East Java were utilised to evaluate the effects of the Household Biogas Program.
5. The data collected is derived from publications retrieved from the Scopus database, encompassing the years 2020 to 2025.

Document Screening and Inclusion Criteria

The documents reviewed were selected for their relevance to three key themes underpinning the development of circular dairy systems. First, they address methods for measuring and predicting resource flows such as nitrogen, phosphorus, water, and energi to support the closure of nutrient and energy loops. Second, they assess dairy farming performance from both economic and environmental perspectives using indicators such as eco-efficiency, technical efficiency, equivalent uniform annual worth, and greenhouse gas emissions. Third, they examine technologies for dairy waste valorisation and the barriers limiting their adoption by smallholder farmers in Indonesia, thereby supporting the study's aim of enhancing sustainability and resilience through closed-loop interventions.

Mass Balance

The Mass Balance method is the most important way to measure resource flows in a closed-loop system. In dairy farming, the goal is to figure out how much Nutrient (N and P) flows and find ways to reduce losses and make Nutrient Use Efficiency (NUE) better. The complex model technique (also called integrated dynamic modeling) gives a complete picture of how materials move through different compartments. This is needed to get a high level of accuracy (MAPE of 16.3%) when predicting resource flows, including the synthesis of organic fertilizer.

Energy Content of By-products

The energy potential of by-products, such as manure, is evaluated by their transformation into biogas or bio-oils/syngas by anaerobic digestion or thermochemical methods like gasification or pyrolysis. As the size of biomass conversions increases, the benefits of using them to make energy by-products should also grow.

Process Flow Model of Self-sufficient Energy

The ideal model integrates waste streams to supply energy and water back into the system, leading to a circular dairy farm system. Key pathways include AD for biogas, and membrane processes (UF/NF) for water recovery from *whey*. The objective is a closed-loop system that reduces pollution and provides net benefits.

RESULT AND DISCUSSION

Dairy Farming Mass Balance (Nutrient Flows)

Cattle farms in Serbia exhibit very low economic efficiency (13.07%), mainly due to persistent technical inefficiencies linked to structural factors. Studies on nitrogen flows, such as those conducted in China, indicate that emissions are the primary pathway of nitrogen loss from animal manure. Long-term sustainability therefore depends on effective mitigation strategies, including improved manure management practices such as low-protein diets and liquid manure injection. Feed innovations, notably the substitution of conventional starch and protein sources with FFP and WDGS, do not reduce feed intake or milk yield. In fact, combining WDGS and FFP increases milk production and improves fibre digestibility.

In dairy farming, recovered products such as bio-slurry, which replaces synthetic fertiliser, or recycled water recovered from *whey* rarely constitute a perfect substitute for virgin inputs due to variances in nutrient concentration, quality constraints, and regulatory hurdles. This calls for future dairy research to acknowledge product differentiation and focus on the valuation of returns rather than assuming perfect equivalence Bantacut & Novitasari, (2016); Pulluru & Akkerman, (2023).

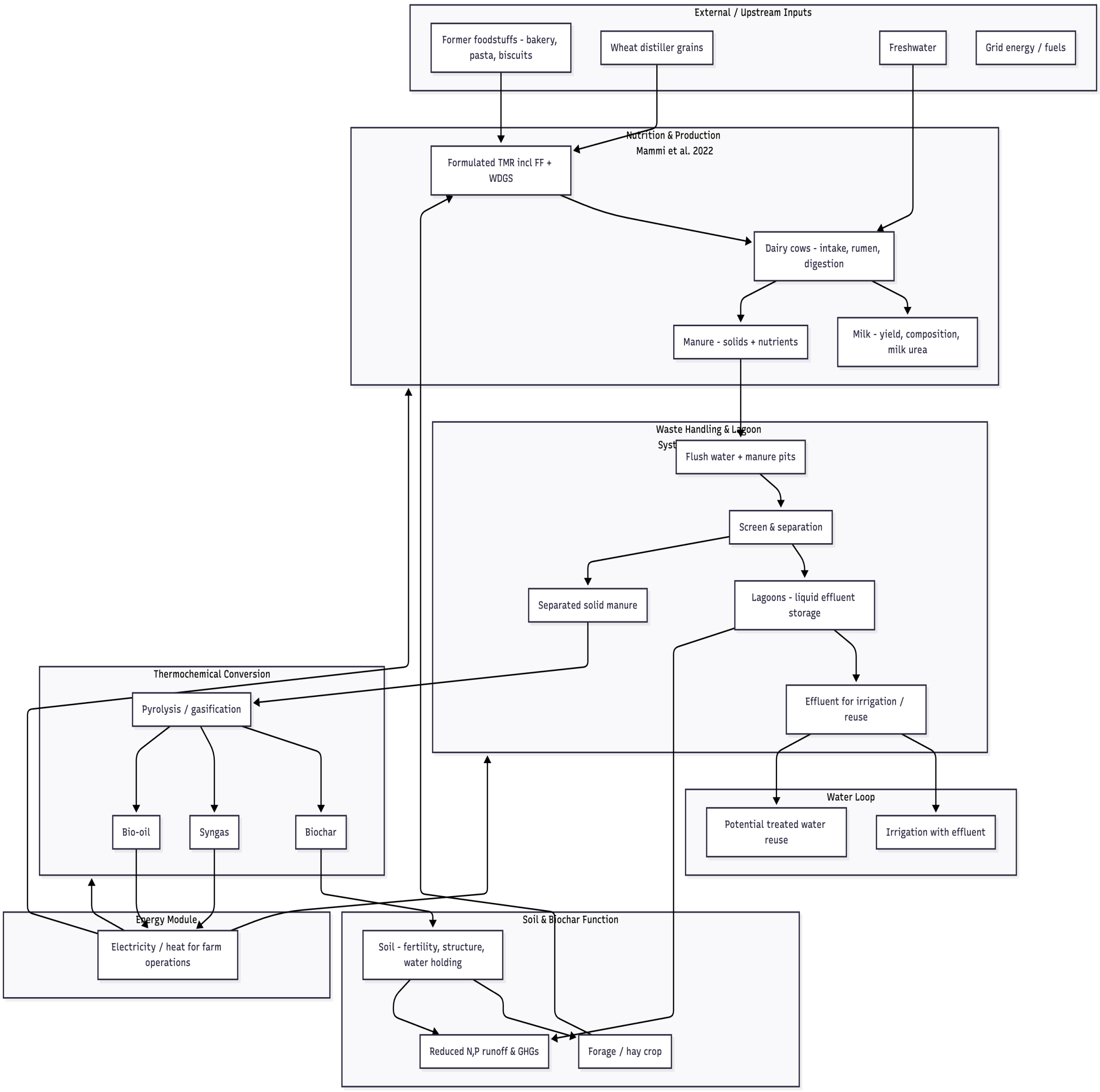

Figure 1. Closed-Loop Dairy Production System: Integrated Resource and Waste Flow Model

Simple Model and Complex Model (Conceptual Application)

The reviewed sources implicitly distinguish between simple and complex analytical approaches based on the depth of system representation. A simple model adopts a conceptual, output-oriented view that focuses only on direct inputs and outputs while overlooking internal processes, feedback, and resource loops; as a result, it is unable to capture the multi-dimensional benefits and trade-offs inherent in Circular Economy interventions. In contrast, a complex model employs integrated System Dynamics or Life Cycle Assessment frameworks to detail internal flows, interactions, and reinforcing or balancing feedback mechanisms. An illustrative example is the Stock–Flow Diagram (SFD) developed for the Taruna Mukti Farmer Group, which models raw material input, production, and marketing subsystems with high structural fidelity. The model achieved a Mean Absolute Percentage Error (MAPE) of 16.3%, categorizing it as a "*good*" forecasting model and demonstrating the robustness and predictive strength of complex, integrated analytical approaches.

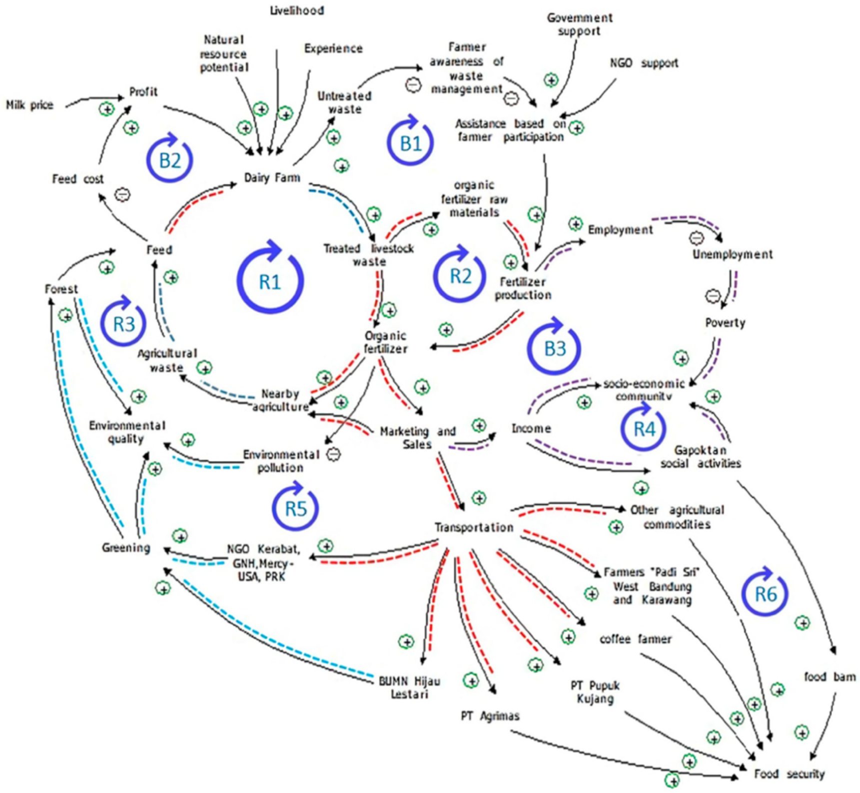

Figure 1. Causal Loop Diagram model on Circular Economy-based dairy cattle waste management (Latif *et al.*, 2023)

Model Description

The models utilised, such as the dynamic system model in Bandung, rely on variables that define the system structure, including raw material input, production, and marketing. A key element is the causal loop diagram (CLD), which shows that the utilisation of agricultural waste as animal feed can reduce dairy cattle feed costs, thereby increasing business profitability (CLD-B2 loop).

Mass Balance Equation (Nutrient Flow)

The most relevant mass balance equation is the Nitrogen (N) Balance at the farm system level, which defines the Nutrient Use Efficiency (NUE). The selected parameters and variables are grounded in their relevance to improving nitrogen (N) balance, which is fundamental to environmental sustainability and the implementation of Circular Economy principles in dairy systems.

The variable $N_{(in)}$ refers to nitrogen supplied through feed, which can be reduced by replacing conventional high-nitrogen inputs with circular feed ingredients such as food processing residues. $N_{(out)}$ represents nitrogen recovered in marketable products like milk and meat, while Nitrogen Use Efficiency (NUE), defined as $N_{(out)}/N_{(in)}$, indicates how efficiently inputs are converted into outputs and is a key target of circular strategies. $N_{(loss)}$ accounts for environmental losses through volatilisation and leaching, which can be mitigated through improved manure management practices. Lastly, $N_{(storage)}$ denotes nitrogen retained within the system, such as in manure storage, which must be properly valorised into fertilisers or energy to close the nutrient loop effectively.

Total Mass (dry basis or as-fed basis)

$$F_{feed} - F_{ort} = F_{intake} \quad (1)$$

$$F_{intake} + F_{water} = F_{milk} + F_{manure} + F_{retained} + F_{emision} \quad (2)$$

Component balances (Carbon, Nitrogen, Phosphorus)

$$F_{intake\ y^{C}_{feed}} = F_{milk}y^{C}_{milk} + F_{manure}y^{C}_{manure} + F^{C}_{emision} + F^{C}_{ret} \quad (3)$$

$$F_{intake\ y^{N}_{feed}} = F_{milk}y^{N}_{milk} + F_{manure}y^{N}_{manure} + F^{N}_{emision} + F^{N}_{ret} \quad (4)$$

$$F_{intake\ y^{P}_{feed}} = F_{milk}y^{P}_{milk} + F_{manure}y^{p}_{manure} + F^{P}_{ret} \quad (5)$$

Waste handling and lagoon (separation and storage)

$$F_{Solid} = \alpha \,.\, F_{manure} \quad (6)$$

$$F_{Liquid} = (1 - \alpha) \,.\, F_{manure} \quad (7)$$

Note: is the fraction captured as separated solids (0–1)

Component mass in each fraction

$$F_{Solid\ y^{N}_{Solid}} + F_{liquid}\ y^{N}_{liquid} = F_{manure}y^{N}_{manure} \quad (8)$$

Lagoon dyanmics (inventory change)

$$\frac{dM_{lagoon}}{dt} = F_{liquid,input} - F_{effluent,output} - F_{reuse} - F_{loss,volatil} - F_{percol} \quad (9)$$

Nutrient fate in lagoon

$$\frac{d(N_{lagoon})}{dt} = F_{liquid} y_{liquid}^{N} - F_{effluent,output} y_{effluent}^{N} - F_{denit} - F_{NH_3,vol} \tag{10}$$

Total conversion mass balance (feedstock basis):

$$F_{\text{feedstock}} = F_{\text{biochar}} + F_{\text{syngas}} + F_{\text{biooil}} + F_{\text{losses}} \tag{11}$$

Component (C) distribution:

$$F_{\text{feedstock}}\, y_{\text{feed}}^{C} = F_{\text{biochar}}\, y_{\text{biochar}}^{C} + F_{\text{syngas}}^{C} + F_{\text{biooil}}^{C} + C_{\text{lost}} \tag{12}$$

Comparison of Complex Model (Critical Review) with Data Output

The integration of circular feeding strategies with whole-farm resource management represents a critical frontier in advancing sustainable dairy production. While the incorporation of former foodstuffs and distiller grains into dairy cow rations addresses efficiency at the nutritional and animal-performance level, farm-scale water energy food waste (WEF–waste) models offer a broader systems perspective capable of transforming manure, water, and energy flows into value-generating cycles. Bringing these two domains together enables a comprehensive understanding of how dietary interventions influence downstream environmental processes, thereby strengthening the conceptual and practical foundations of closed-loop dairy systems.

Table 1. Comparative Critical Review

Dimension	Combined Inclusion of Former Foodstuff & Distiller Grains (FF + WDGS)	Farm-scale WEF–Waste Nexus Closed-loop Dairy System	Critical Commentary
Primary Objective	Assess effects of circular feed ingredients (FF, WDGS) on milk performance, rumen parameters, and fibre digestibility.	Develop a system-based WEF nexus tool to model water, energy, manure, nutrient flows, and evaluate closed-loop resource optimisation.	FF/WDGS optimises animal nutrition, while WEF system optimises whole-farm resource flows across water, energy, food, and waste.
System Boundary	Micro-level (individual cow). Controlled Latin-square design with 8 cows.	Meso-level (400-cow dairy farm). Full manure, water, energy, crop cycles.	The studies operate at very different scales: animal vs.

Dimension	Combined Inclusion of Former Foodstuff & Distiller Grains (FF + WDGS)	Farm-scale WEF–Waste Nexus Closed-loop Dairy System	Critical Commentary
			farm-system modelling.
Circularity Approach	Upcycling bakery waste and distiller grains into animal feed to reduce reliance on cereals and soy.	Converting manure into biochar, syngas, bio-oil; integrating filtered lagoon effluent and closed-loop soil nutrient cycling.	FF/WDGS equal to substitutional circularity; WEF equal to transformative circularity through thermochemical conversion.
Technological Components	Feed formulation software, digestibility assays, rumen pH/VFA analysis, controlled diets.	Pyrolysis/gasification reactors, wastewater sampling, lagoon modelling, irrigation and nutrient flow modelling.	FF/WDGS uses biological or animal science tech; WEF uses engineering and environmental system modelling.
Key Inputs	Former foodstuffs (pasta, bread, biscuits), wheat distiller grains, conventional TMR.	Manure, lagoon wastewater, crop fields, pyrolysis/gasification systems.	FF/WDGS affects nutrient intake biometrically; WEF affects waste/resource flows environmentally.
Key Outputs	- Higher milk yield (with FF+WDGS)		

The two studies examine complementary levels of circularity in dairy systems, ranging from cow-level nutrition to farm-scale resource management. Mammi *et al*., (2022) show that incorporating former foodstuffs and wheat distiller grains into dairy rations can sustain or improve milk yield while enhancing nitrogen-use efficiency and reducing reliance on conventional feed resources. In contrast, Muell *et al.*, 2022 focus on post-excretion processes, modelling a closed-loop dairy system in which manure is converted into biochar and energy, improving nutrient recycling, water reuse, and environmental performance. Together, the studies illustrate how feed valorisation and waste-to-resource technologies can form an integrated circular dairy framework. While dietary interventions are relatively low-cost and readily adoptable, closed-loop WEF systems require higher capital investment but deliver broader environmental benefits. However, both approaches remain weakly connected, as dietary effects on manure quality and farmer adoption behaviour are not fully addressed. Future research should integrate animal nutrition, manure management, and socio-institutional factors to support holistic circular dairy system design.

In summary, integrating the FF and WDGS nutrition model with the farm-scale WEF waste nexus model yields a coherent, multi-level circular dairy framework. At the cow level, circular feeds upcycle industrial co-products while sustaining or improving production performance. At the farm level, manure is transformed into energy and biochar, enabling water reuse, nutrient recycling and soil restoration. Together, these interventions offer a pathway towards a more resource-efficient, low-waste dairy system, provided that the biological, technological and socio-economic interactions between them are explicitly considered and empirically validated.

Determining Energy and Water Surplus from Waste Treatment

Resource recovery has emerged as a cornerstone of modern circular economy strategies within the dairy and livestock sectors. By transforming waste streams into valuable inputs, these systems not only reduce environmental burdens but also create tangible economic benefits for farmers and rural communities. One of the most prominent examples is the anaerobic digestion of animal manure, which enables the production of biogas as a renewable household energy source. For small-scale farmers, this technology yields Equivalent Uniform Annual Benefits (EUAW) ranging from USD 825 to USD 1,056 per year, demonstrating its strong economic viability. Evidence from East Java further illustrates that the adoption of biogas can displace nearly all Liquefied Petroleum Gas (LPG) consumption in participating households, lowering average household energy expenditure by approximately 45 percent and improving long-term energy security. Beyond energy recovery, water recirculation technologies are increasingly recognised for their substantial contribution to resource self-sufficiency and operational efficiency across dairy value chains.

Water quality (nutrient) balance in reuse:

$$F_{\text{irrig}}\, y^{N}_{\text{irrig}} = r \cdot F_{\text{effluent,out}}\, y^{N}_{\text{effluent}} \quad (13)$$

Advanced membrane technologies in cheese production enable whey permeate to be recovered and reused as clean water for cleaning, sanitation, and irrigation, reducing freshwater demand and strengthening circular economy practices. More broadly, growing pressure on natural resources, stricter environmental regulations, and rising input costs are driving dairy producers to adopt integrated resource recovery strategies. The combined use of water recycling, waste-to-energy systems, and nutrient recovery supports sustainable intensification by lowering emissions, improving efficiency, and enhancing farm resilience. However, adoption remains uneven, as smallholders face financial and technical barriers while larger farms encounter regulatory and integration challenges. Therefore, a holistic understanding of the economic, environmental, and operational implications of resource recovery is essential to support scalable, circular dairy systems that are both economically viable and environmentally sustainable.

Surplus Energy based on Manure Processing (*Filter Cake* Analogy)

Thermochemical processes such as pyrolysis and gasification offer a viable pathway for converting animal manure, which behaves similarly to dense filter cake or biomass, into valuable energy by-products. Through these processes, manure can be transformed into syngas and bio-oil, both of which have potential applications as renewable energy sources within farm operations. The solid residue, known as biochar, provides additional value as a soil amendment capable of improving nutrient retention and soil structure. These conversion technologies also contribute to reducing the environmental burden of raw manure by stabilising organic matter and lowering greenhouse gas emissions. When integrated into farm systems, the recovered energy products can support electricity generation, heating, or fuel substitution, thereby reducing dependence on external energy inputs.

Biogas from AD

$$E_{\text{biogas}} = F_{\text{biogas}} \cdot LHV_{\text{biogas}} \tag{14}$$

where LHV is lower heating value ($\text{MJ} \cdot \text{m}^{-3}$ or $\text{MJ} \cdot \text{kg}^{-1}$).

Syngas / bio-oil energy:

$$E_{\text{syn}} = F_{\text{syngas}} \cdot LHV_{\text{syngas}}, E_{\text{biooil}} = F_{\text{biooil}} \cdot LHV_{\text{biooil}} \tag{15}$$

Energy balance:

$$E_{\text{prod}} = E_{\text{biogas}} + E_{\text{syn}} + E_{\text{biooil}} \tag{16}$$

$$E_{\text{net}} = E_{\text{prod}} \cdot \eta_{\text{conv}} - E_{\text{demand}} - E_{\text{losses}} \tag{17}$$

where η_{conv} is conversion efficiency (generator, boiler).

Whole-farm mass balance for a component (e.g. N):

$$\sum \text{N inputs}_{\text{farm}} = \sum \text{N outputs}_{\text{farm}} + \Delta N_{\text{farm,stock}} \quad (18)$$

where inputs = feed N, fertiliser N, deposition; outputs = milk N exported, sold manure/biochar, volatilisation, denitrification losses, off-farm discharge; $\Delta N_{\text{farm,stock}}$= change in soil/stock N pools.

$$F_{feed} y^{N}_{feed} + F^{N}_{fert} = F_{milk} y^{N}_{milk} + F^{N}_{Sold\ Biochar} + F_{effluent,output} y^{N}_{effluent} + F_{NH_3,volume} + F_{denit} + \Delta N_{Solid} \quad (19)$$

The biochar produced can be applied to agricultural fields, contributing to long-term soil fertility and carbon sequestration. Importantly, thermochemical conversion systems tend to exhibit improved efficiency and cost-effectiveness when deployed at larger operational scales. As farm size increases, the volume of available manure rises, enabling more continuous and economically viable operation of pyrolysis or gasification units. Larger farms also benefit from economies of scale in terms of equipment investment, energy recovery, and operational integration. Consequently, the overall benefits of converting manure-derived biomass into energy by-products are expected to grow substantially as the size and capacity of the farm expand.

Alternative Technologies for *Filter Cake* Utilisation

Advanced waste-to-resource technologies beyond composting are crucial for adding value to manure and digestate. Thermochemical processes such as pyrolysis and gasification convert solid waste into biochar, which can improve soil quality, remove nutrients from wastewater, and enhance phosphorus retention. Anaerobic digestion is a strong alternative to composting, as it operates with fewer nutrient balance constraints and produces biogas as a renewable energy source. The resulting digestate is rich in nitrogen and phosphorus, making it suitable for targeted nutrient recovery, particularly through struvite precipitation. Overall, these technologies enable fertiliser recovery, reduce nutrient pollution, and improve the environmental and economic performance of livestock systems.

Potential By-product to Supply Energy of Biomass

The primary by-product with energy generation potential in dairy production systems is manure, which can be converted into biogas through anaerobic digestion (Haryanto *et al.*, 2025; Bedi *et al.*, 2017). This process enables farms to produce renewable energy while simultaneously managing waste more sustainably. Beyond dairy manure, other biological wastes also represent valuable feedstocks for energy conversion. Slaughterhouse by-products, such as paunch manure and digestive tract contents, are increasingly recognised for their substantial biochemical potential. These materials contain notably high levels of crude protein, with published literature reporting concentrations reaching up to 90 percent. Such a high protein content indicates a rich supply of organic matter suitable for biogas production (Orner *et al.*, 2021).

In addition to energy recovery, these wastes may offer supplementary nutritional value when used appropriately within integrated waste management systems. Their utilisation can reduce the reliance on conventional feedstocks and external energy sources. Incorporating these diverse organic materials into anaerobic digestion can enhance the overall efficiency and output of biogas systems. Consequently, expanding the feedstock base beyond dairy manure strengthens both the energy resilience and environmental performance of livestock operations.

Potential Energy Production from By-product Utilisation

The utilisation of manure for biogas production offers substantial economic benefits by replacing fossil fuels such as Liquefied Petroleum Gas (LPG). When households or farms substitute LPG with biogas, they experience direct cost savings that accumulate over time. Beyond the financial advantages, biogas systems also contribute significantly to climate mitigation efforts. During controlled anaerobic digestion, methane that would otherwise escape into the atmosphere is captured and converted into usable energy. This process results in meaningful carbon offsets, as methane is a greenhouse gas with a global warming potential far higher than that of carbon dioxide. By transforming methane into energy rather than allowing it to be emitted, biogas systems effectively reduce the overall carbon footprint of livestock operations.

The magnitude of these environmental benefits depends largely on the volume of methane captured and utilised. From an economic standpoint, the profitability of biogas systems is strongly influenced by the yield of biogas produced from the manure. Higher biogas yields translate directly into greater energy substitution and higher cumulative savings. As a result, both the climate benefits and economic performance of biogas technologies are closely linked to the efficiency of the digestion process.

Policy Implications

Effective policy intervention is essential to accelerate the transition towards a circular economy within the livestock and dairy sectors. One of the most significant challenges faced by Indonesian smallholders is the high initial investment cost of biogas systems, which currently ranges from USD 1,000 to USD 1,200. Many farmers have expressed the desire for this cost to be reduced to a more affordable level of USD 300 to USD 400, highlighting the need for targeted financial support mechanisms. A key recommendation emerging from recent analyses is the reallocation of a portion of the existing LPG subsidy budget to help fund biogas installations. Such a strategy would create a direct incentive for farmers to shift away from fossil fuel dependence and would substantially improve the payback period of biogas systems (Haryanto *et al.*, 2025).

Policy efforts must also consider the value of bio-slurry, as evidence suggests a positive albeit not statistically significant association between digester ownership and higher farm revenues. This indicates that governments should support further research on optimal application practices, efficient transport systems, and the development of markets for digestate as a substitute for chemical fertilisers and pesticides. Addressing persistent structural inefficiencies is equally important, as these inefficiencies impede both technical performance and eco-efficiency at the farm level. Strengthening managerial capacity, improving knowledge transfer, and providing tailored extension services can help overcome these long-standing constraints. When combined, these policy measures form a comprehensive framework that can significantly enhance the adoption and effectiveness of circular economy technologies in smallholder farming systems.

Schematic Diagram of Self-Sufficient Biomass Production Process (Conceptual Dairy CE Loop)

A closed-loop dairy system relies on the seamless integration of multiple resource flows. This integration ensures that water, energy, nutrients, and waste are continuously recycled to support a self-sustaining production cycle. The closed-loop dairy system requires the integration of resource flows are present in Table 2.

Table 2. Closed-loop dairy system

System Component	Input	Process	Output	CE Function
Feed Management	FFP/WDGS	Ruminant Digestion	Milk, Manure	Reduces land occupation, improves sustainability.
Manure Management	Manure	Anaerobic Digestion (AD)	Biogas (Energy), Digestate (Bio-slurry/Nutrients).	Energy self-sufficiency, carbon offset.
Water & Nutrient Recovery	Whey, Liquid Digestate	UF/NF (Membranes), Struvite Precipitation	Clean Water, Recovered P (Fertiliser)	Water reuse, mitigates eutrophication.
Soil/Crop System	Bio-slurry/Biochar	Fertilisation, Soil Amendment	Forage/Feed	Closes nutrient loop, replaces chemical fertilisers.

The system is designed to utilise the recovered biogas as a renewable source of energy for cooking or electricity generation. By doing so, it reduces dependence on conventional fossil fuels and lowers household or farm energy costs. The recovery of biogas also contributes to improved energy security, particularly in rural areas where access to stable energy supplies may be limited. In parallel, the system captures and treats wastewater so that it can be reused safely within farm operations (Atasu *et al.*, 2008).

This recovered water can be directed towards equipment rinsing, thereby reducing the need for fresh water in routine cleaning activities. It can also be applied to agricultural fields as irrigation, helping to sustain crop production in water-constrained environments. The dual recovery of energy and water strengthens the resource efficiency of the entire dairy system. These practices align closely with the principles of circular economy by ensuring that materials are continuously reused rather than discarded. As a result, waste streams are transformed into valuable inputs that support ongoing production. Ultimately, this integrated approach enhances environmental sustainability while providing practical economic benefits to farming communities.

CONCLUSION

Many regions' dairy farms still exhibit low levels of eco-efficiency, as evidenced by Serbian systems that only operate at 13.07 percent efficiency. This performance level suggests that strategic intervention is urgently needed. Farm operations' long-standing structural and administrative constraints are mostly to blame for the inefficiency. These flaws limit prospects for sustainable growth, increase environmental consequences, and limit productivity. So, to improve total technological efficiency, it is important to improve the skills of managers. Another important factor in the modernization of the dairy industry is economic viability. Integrated manure management techniques, like anaerobic digestion and nitrogen recovery by struvite precipitation, have been demonstrated to save a lot of money.

Equivalent Uniform Annual Worth (EUAW) values might be as high as $1,056 USD annually in certain situations. These profits show how valuable circular manure systems can be. Additionally, they provide significant environmental benefits by lowering nitrogen losses and assisting in the development of carbon-negative farm layouts. The usage of biogas increases farm and family resilience even further. Using biogas instead of liquefied petroleum gas can significantly lessen a family's reliance on fossil fuels. Household energy costs often decrease by about 45% as a result of this shift.

Circularity in feed and water is also essential to sustainable dairy operations. Utilizing circular feedstuffs, like leftover food items and wheat distiller grains, can preserve or even raise the quality and quantity of milk. Clean water recovery is also made possible by membrane technologies used on whey streams. It is possible to cut freshwater use by up to 90% with such mechanisms. There are still significant policy obstacles in place despite these encouraging advancements.

The most important of them in Indonesia is the high initial cost of setting up small-scale biogas digesters. The average investment of $1,000 to $1,200 USD is out of reach for many smallholders. As a result, targeted subsidies and financial assistance are necessary to facilitate broad adoption.

Recommendations

Financial policy reform is essential if smallholder farmers are to adopt biogas technologies at scale. At present, the high upfront investment required for a digester represents a major barrier to adoption. Many farmers simply cannot afford the initial cost, which typically ranges from 1,000 to 1,200 US dollars. One effective strategy would be for the government to reallocate a portion of existing LPG subsidies towards biogas installations. Such a shift would allow the subsidised price of digesters to fall into the more affordable range of 300 to 400 US dollars. This reduced investment threshold would make biogas systems financially viable for a far wider group of smallholders. Lowering the cost barrier would not only stimulate adoption but also accelerate the transition away from fossil fuel dependence.

Alongside financial reform, it is equally important to enhance the utilisation of bio-slurry, the nutrient-rich by-product of anaerobic digestion. Current evidence suggests that, although bio-slurry offers agronomic value, its contribution to overall farm revenue has not yet reached statistical significance. This is partly due to limited knowledge regarding appropriate application techniques. To address this, public policy must support targeted research aimed at identifying the most effective methods of using bio-slurry as a full substitute for chemical fertilisers and pesticides. Extension services will play a key role in disseminating these findings to farmers. Improving bio-slurry management has the potential to create substantial savings in input costs. Over time, more efficient utilisation could strengthen the financial case for biodigester adoption.

In addition to financial and agronomic interventions, structural improvement within the dairy sector is crucial. Many farms continue to experience persistent inefficiencies that stem from weaknesses in their organisational and managerial systems. These structural issues are a major contributor to low eco-efficiency scores. Technical assistance therefore needs to be directed towards strengthening institutional capacity. Training programmes and advisory support can help farmers adopt more efficient practices. By addressing these underlying constraints, policy interventions can significantly enhance both technical and environmental performance.

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