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Material Flow Cost Accounting (MFCA)-Driven Smart Goat Livestock Management System

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ABSTRACT

The livestock sector plays a crucial role in food security and rural economic resilience; however, goat farming management in developing economies remains largely traditional and weakly integrated with structured environmental accounting systems. This study develops and validates a Material Flow Cost Accounting (MFCA)-Driven Smart Goat Livestock Management System, which integrates environmental management accounting, Internet of Things (IoT) monitoring, emission estimation, and artificial intelligence (AI)-based decision support within a unified digital platform. Using a design science research approach combined with field validation, the system was implemented in a medium-scale goat farm over a two-month period. The MFCA model quantified material inputs and outputs in both physical and monetary terms, including feed conversion, waste generation, and methane (CH_4) and nitrous oxide (N_2O) emissions based on IPCC Tier 1 guidelines. The results demonstrate improvements in feed efficiency (from 74% to 84%), mortality reduction (from 8% to 4%), increased data accuracy (from 60% to 92%), and a 22% improvement in eco-efficiency ratios. The AI module achieved 87% accuracy in estrus detection and 84% accuracy in early disease classification. The study extends MFCA application from manufacturing to biological production systems and introduces the concept of accounting-driven smart farming, where environmental accounting is embedded within digital infrastructure. The findings contribute to the advancement of Digital Environmental Management Accounting (Digital EMA) and provide a scalable model for sustainable livestock transformation in emerging economies.

Keywords: Material Flow Cost Accounting (MFCA); Environmental Management Accounting; Smart Farming; IoT-Based Livestock Management; Eco-Efficiency; Emission Accounting; Artificial Intelligence; Digital Green Accounting

Field: Environmental Management Accounting; Management Accounting Innovation; Sustainable Agriculture and Livestock Systems; Digital Accounting Systems; Smart Farming Technology; Sustainability and Climate Accounting

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SDGs: Zero Hunger (2); Industry, Innovation and Infrastructure (9); Responsible Consumption and Production (12); Climate Action (13); Decent Work and Economic Growth (8)

INTRODUCTION

The livestock sector plays a strategic role in strengthening food security, rural income generation, and local economic resilience (Nassar, 2026). In many developing countries, including Indonesia, goat farming represents a significant component of small- and medium-scale agribusiness. However, despite its economic potential, goat livestock management remains largely traditional, fragmented, and weakly supported by structured accounting systems. Most farmers rely on manual records, lack real-time performance monitoring, and rarely integrate environmental cost considerations into managerial decision-making.

Simultaneously, global sustainability agendas increasingly demand measurable accountability in agricultural production (Macdonald et al., 2024). Livestock activities contribute to greenhouse gas emissions, particularly methane (CH_4) and nitrous oxide (N_2O), and generate material inefficiencies in feed conversion and waste handling. While environmental awareness is rising (Renaldo, Fadrul, et al., 2022), the sector still lacks integrated systems capable of linking operational data, cost structures, and environmental impact into a unified decision-making framework. As a result, financial performance and environmental performance are often managed separately, limiting the ability of farmers to achieve eco-efficiency.

Material Flow Cost Accounting (MFCA), as an environmental management accounting tool, offers a structured approach to tracing material inputs, product outputs, and non-product outputs (waste and emissions) in both physical and monetary units (Usul & Olgun, 2025). MFCA enables organizations to identify hidden inefficiencies by assigning costs not only to finished products but also to material losses. Although MFCA has been widely applied in manufacturing industries, its implementation in livestock farming, particularly goat farming, remains extremely limited. Existing smart farming solutions primarily focus on IoT-based monitoring or AI-driven disease detection without embedding systematic cost accounting frameworks. Consequently, technological innovation in livestock management has not yet fully incorporated environmental accounting principles.

This study introduces a Material Flow Cost Accounting (MFCA)-Driven Smart Goat Livestock Management System, an integrated digital platform that positions MFCA as the core analytical engine of livestock management (Tran & Herzig, 2020). Unlike conventional smart farming systems that emphasize sensor-based monitoring alone, this system integrates Internet of Things (IoT) sensors, cloud-based dashboards, and AI-based decision support with a structured MFCA model. Feed consumption, weight gain, waste generation, and emission estimations are translated into both physical metrics and monetary values, enabling real-time eco-efficiency analysis.

The novelty of this research lies in four key contributions. First, it reconceptualizes goat farming as a biological manufacturing system, where material flows (feed–growth–waste–emission) are systematically quantified using MFCA principles. Second, it integrates environmental cost accounting with IoT-generated real-time data, allowing dynamic rather than static cost analysis. Third, it incorporates emission estimation (CH_4 and N_2O) within the MFCA structure, linking environmental externalities to managerial accounting reports. Fourth, it embeds artificial intelligence to enhance predictive decision-making while maintaining cost transparency grounded in accounting logic.

By bridging environmental management accounting and smart agriculture technology, this research contributes to the advancement of digital green accounting in the livestock sector (Renaldo, Hafni, et al., 2022). The system not only improves operational efficiency and cost control but also strengthens sustainability reporting and supports data-driven policy integration. In doing so, it addresses the critical gap between technological innovation and accounting-based sustainability management in small- and medium-scale livestock enterprises.

LITERATURE REVIEW

Environmental Management Accounting in the Agricultural Sector

Environmental Management Accounting (EMA) integrates environmental considerations into internal decision-making processes by linking physical material flows with monetary information (Swalih et al., 2024). EMA shifts managerial focus from traditional financial accounting toward eco-efficiency, cost transparency, and sustainability-oriented performance measurement. In agricultural contexts, EMA is increasingly recognized as a strategic instrument for improving resource efficiency (Renaldo et al., 2025), reducing environmental impact, and strengthening long-term competitiveness.

However, empirical implementation of EMA in livestock farming remains limited. Most small- and medium-scale farms rely on conventional bookkeeping systems that emphasize revenue and direct expenses while neglecting material losses, waste costs, and emission-related externalities. This creates a structural gap between sustainability objectives and managerial accounting practices in the livestock sector.

Material Flow Cost Accounting (MFCA)

Material Flow Cost Accounting (MFCA) is a core tool within EMA that tracks material inputs and outputs in both physical and monetary units (Walls et al., 2023). Standardized under ISO 14051, MFCA classifies outputs into: Positive products (desired outputs) and Negative products (material losses, waste, emissions).

The central principle of MFCA is that material losses carry significant hidden costs, including raw material costs, energy costs, and system costs. By allocating financial value to non-product outputs, MFCA reveals inefficiencies that are often invisible in traditional cost accounting systems.

MFCA has been widely applied in manufacturing industries such as automotive, electronics, and food processing. Studies show that MFCA improves resource productivity, reduces waste, and enhances environmental transparency. Nevertheless, its application in biological production systems, particularly goat livestock farming, remains underexplored.

Unlike manufacturing processes where material flows are mechanically controlled, livestock farming involves biological conversion processes (feed-to-weight gain-to-waste-to-emission). Therefore, adapting MFCA to goat farming requires reconceptualizing livestock operations as a biological material flow system. This represents a significant theoretical extension of MFCA beyond industrial settings.

Smart Farming and IoT-Based Livestock Management

The emergence of smart farming technologies has transformed agricultural management (Said Mohamed et al., 2021). Internet of Things (IoT) sensors, cloud computing, and data analytics enable real-time monitoring of environmental conditions, animal health, and productivity indicators.

In goat livestock management, IoT applications commonly include: Body temperature monitoring, Weight tracking through smart scales, Activity detection for estrus identification, Air quality monitoring in barns. While these technologies improve operational control and disease detection, most smart farming systems prioritize technical monitoring rather than structured cost analysis. Financial evaluation remains separate from real-time production data. Consequently, although farmers receive performance insights, they lack integrated cost-efficiency analysis grounded in accounting principles.

This fragmentation highlights a critical gap: digital livestock technologies rarely embed environmental management accounting frameworks within their architecture.

Artificial Intelligence in Decision Support Systems (DSS)

Artificial Intelligence (AI), particularly machine learning algorithms such as Random Forest and Convolutional Neural Networks (CNN), has been increasingly applied in livestock management (Zhu et al., 2025). AI-based Decision Support Systems (DSS) assist farmers in: Early disease detection, Estrus prediction, Feed optimization, and Mortality risk forecasting (Renaldo et al., 2023).

These systems enhance predictive accuracy and reduce reactive management practices. However, existing AI-DSS models are primarily performance-oriented, focusing on biological indicators rather than economic efficiency or environmental cost integration.

There remains limited integration between AI-driven predictive analytics and structured accounting systems. As a result, technological decision-making lacks cost transparency and eco-efficiency measurement.

Sustainability Reporting and Emission Accountability in Livestock Farming

Livestock farming contributes to greenhouse gas emissions, especially methane (CH_4) and nitrous oxide (N_2O) (Pence et al., 2024). International sustainability frameworks increasingly require emission measurement, carbon reporting, and traceability in agricultural supply chains.

Despite this growing demand, small-scale livestock farms rarely possess systems capable of calculating and reporting emissions in quantifiable and monetized formats. Emission estimation is often conducted at the macro-policy level rather than embedded within farm-level managerial systems.

Integrating emission calculations into MFCA structures allows environmental impacts to be translated into cost-related insights, strengthening accountability and supporting sustainability-oriented decision-making.

Research Gap and Theoretical Positioning

Based on the reviewed literature, several gaps are identified:

1. MFCA has been extensively applied in manufacturing but remains underdeveloped in biological livestock systems.
2. Smart livestock technologies emphasize monitoring and prediction but lack integration with structured environmental cost accounting.
3. AI-based DSS improves productivity but rarely incorporates MFCA-based cost and emission analysis.
4. Sustainability reporting in livestock farming is not systematically embedded within real-time management platforms.

Therefore, this study addresses a critical interdisciplinary gap by integrating:

1. MFCA as the accounting engine
2. IoT for real-time physical data acquisition

3. AI for predictive decision support
4. Emission estimation within cost accounting structures

This integration advances the theoretical development of environmental management accounting by extending MFCA into biological production systems and embedding it within digital smart farming architecture.

METHODOLOGY

Research Design

This study adopts a design science research (DSR) approach combined with a field validation method (Weggeman & Cauffman, 2024). The design science paradigm is appropriate because the objective is not only to analyze phenomena but also to develop and validate an innovative artifact, namely, the MFCA-Driven Smart Goat Livestock Management System.

The research consists of three main phases:

1. System Design and Development
2. MFCA Model Integration and AI Modeling
3. Field Implementation and Validation

This approach enables the development of a functional digital accounting system while empirically testing its operational and eco-efficiency performance in a real livestock environment.

System Architecture Development

The system architecture is developed using a multi-layer framework, consisting of:

a. Physical Layer (IoT Data Acquisition)

Sensors are installed in the goat farm to collect real-time data, including: Body temperature, Weight measurements, Activity levels, and Barn environmental conditions (temperature, humidity, air quality). Microcontrollers transmit data via Wi-Fi to a cloud server.

b. Data Management Layer (Cloud-Based Infrastructure)

A cloud database stores and processes real-time data. Backend development uses API integration to ensure data synchronization between IoT devices, MFCA modules, and AI algorithms.

c. Accounting and Analytics Layer

This layer embeds the MFCA model and emission calculation algorithms into the system dashboard. The platform converts physical input-output data into monetary values for cost analysis.

d. Decision Support Layer

Machine learning algorithms (Random Forest and CNN) are trained to detect estrus and early disease symptoms. Predictive results are integrated into the dashboard to support managerial decision-making.

MFCA Model Implementation

The MFCA model follows ISO 14051 principles and consists of the following steps:

Step 1: Identification of Material Inputs and Outputs

Material inputs include: Feed consumption, Water usage, Energy consumption. Outputs are classified into: Positive product: weight gain and livestock growth; Negative product: manure, unused feed, methane (CH_4), and nitrous oxide (N_2O) emissions.

Step 2: Quantification in Physical Units

All flows are measured in kilograms or equivalent units per goat per month.

Step 3: Monetary Valuation

Costs are allocated into four categories: Material cost, Energy cost, System cost, Waste management cost. Material loss costs are calculated to identify hidden inefficiencies.

Step 4: Eco-Efficiency Analysis

Eco-efficiency indicators are computed using:

$$Eco - Efficiency = \frac{Economic\ Value\ (Output)}{Environmental\ Impact\ (Material\ Loss + Emissions)}$$

Emission calculations for CH_4 and N_2O follow IPCC Tier 1 guidelines and are integrated into the MFCA cost structure.

AI Model Development

The AI module is developed using supervised machine learning techniques:

a. Data Collection

Sensor data from 25 goats are collected over a two-month period.

b. Data Preprocessing

Cleaning missing values

Normalization

Labeling (healthy vs. sick; estrus vs. non-estrus)

c. Model Training

Two algorithms are used:

- Random Forest (classification of health status)
- Convolutional Neural Network (pattern detection from time-series activity data)

d. Performance Evaluation

Model accuracy, precision, recall, and F1-score are calculated.

The minimum acceptable accuracy threshold is set at 80%.

5. Field Testing and Validation

Field validation is conducted at a medium-scale goat farm. The evaluation focuses on:

a. Operational Efficiency
    - Reduction in feed waste
    - Improvement in feed conversion rate
b. Cost Efficiency
    - Reduction in material loss cost
    - Improvement in cost transparency
c. Environmental Performance
    - Measured CH_4 and N_2O emission estimates
    - Eco-efficiency improvement rate
d. System Performance
    - System uptime (target $\geq$ 90%)
    - User satisfaction survey

Pre- and post-implementation comparisons are conducted to measure improvements in efficiency and cost control.

Data Analysis Techniques

The study employs:

- Descriptive statistical analysis for operational performance
- Comparative analysis (before vs. after system implementation)
- Cost variance analysis under MFCA
- AI model evaluation metrics
- Eco-efficiency ratio analysis

Quantitative results are interpreted to assess whether the system improves productivity, reduces material losses, and enhances sustainability reporting capability.

Ethical and Data Considerations

All field data are collected with farm owner consent (Renaldo, Fransisca, Junaedi, Nyoto, et al., 2024). The system is designed to ensure data confidentiality and secure cloud storage. The research does not involve invasive animal experimentation beyond routine farm monitoring.

Methodological Contribution

This methodology contributes by operationalizing MFCA within a digital IoT-AI architecture, transforming static environmental accounting into a real-time decision-support mechanism. The integration of biological production data with cost allocation and emission modeling represents an advancement in environmental management accounting applications.

RESULTS AND DISCUSSION

Result

System Implementation Outcomes

The MFCA-Driven Smart Goat Livestock Management System was successfully implemented in a medium-scale goat farm consisting of 25 goats over a two-month validation period. The system operated with an average uptime of 93%, exceeding the minimum target of 90%. Real-time data from IoT sensors were consistently transmitted to the cloud-based dashboard, enabling continuous monitoring of feed consumption, weight gain, barn conditions, and animal activity.

The integration between the IoT layer, MFCA module, and AI-based decision support system functioned without major synchronization errors. Data buffering mechanisms minimized connectivity disruptions, ensuring data continuity for cost and emission analysis.

MFCA-Based Cost Transparency and Material Flow Analysis

The implementation of MFCA revealed previously hidden inefficiencies in feed utilization and waste generation. Prior to system adoption, feed efficiency was estimated at approximately 74%. After applying real-time monitoring and MFCA-based tracking, feed efficiency increased to 84%.

From a cost perspective, the system identified that approximately 16% of feed input was categorized as non-product output (material loss). When monetized, this loss represented a significant hidden cost component that had not been explicitly measured under conventional accounting practices.

By assigning monetary value to material losses (Renaldo, Fransisca, Junaedi, Tanjung, et al., 2024), the system enabled farmers to:

- Identify overfeeding patterns
- Adjust feed composition
- Reduce unnecessary procurement

Overall, feed-related cost inefficiency decreased by approximately 10% during the observation period. This finding supports the theoretical proposition that MFCA enhances cost visibility and improves eco-efficiency in biological production systems. Unlike traditional bookkeeping, which aggregates expenses at the end of the period, the MFCA-driven system provided continuous cost-flow analysis.

Emission Estimation and Environmental Performance

Emission calculations based on IPCC Tier 1 guidelines were integrated within the MFCA framework. The average emission estimates were:

- Methane (CH_4): 2.9 kg CO_2-eq per goat per month
- Nitrous oxide (N_2O): 0.8 kg CO_2-eq per goat per month

These values remained within efficient operational thresholds for small-scale goat farming. Importantly, emission data were not treated as standalone environmental metrics but embedded within the cost structure. This integration allowed emission-related material losses to be evaluated economically, reinforcing the connection between environmental impact and financial performance. The eco-efficiency ratio improved by approximately 22% after system implementation, indicating better economic output relative to environmental burden.

AI Decision Support System Performance

The AI module achieved:

- 87% accuracy in estrus detection
- 84% accuracy in early disease symptom classification

The integration of predictive analytics reduced mortality rates from 8% to 4%, representing a 50% decrease. Early detection enabled timely intervention, lowering treatment costs and productivity loss.

Unlike standalone AI monitoring systems (Junaedi et al., 2024), the predictive output was linked to MFCA cost data. For example:

- Disease alerts triggered cost impact projections
- Estrus detection informed breeding cycle efficiency analysis

This demonstrates that AI enhanced not only biological performance but also cost-informed decision-making.

Operational Efficiency Improvements

Comparative analysis before and after system implementation showed:

Table 1. Comparative Analysis

Indicator	Before System	After System	Improvement
Feed Efficiency	74%	84%	10%
Mortality Rate	8%	4%	-50%
Daily Recording Time	45 minutes	10 minutes	-78%
Data Accuracy	60%	92%	32%

The reduction in manual recording time indicates digital process efficiency. Improved data accuracy strengthened financial reporting reliability and sustainability documentation capability.

Discussion

This study demonstrates that integrating Material Flow Cost Accounting (MFCA) within a smart livestock management architecture fundamentally reshapes how goat farming performance is measured and managed. The findings highlight not only operational improvements but also a structural transformation in managerial logic, from reactive production monitoring to accounting-driven eco-efficiency management.

Extending MFCA to Biological Production Systems

Traditionally, MFCA has been applied in manufacturing industries where material flows are mechanically controlled and predictable. This study extends MFCA into a biological production context, where feed conversion, weight gain, waste generation, and emissions are influenced by living organisms.

The results indicate that goat farming can be conceptualized as a biological manufacturing system, in which feed serves as raw material, livestock growth as positive output, and manure and emissions as negative outputs. By monetizing these flows, the system reveals hidden inefficiencies that are typically embedded within aggregate feed expenses.

This extension contributes theoretically by demonstrating that MFCA is adaptable beyond industrial processes and can be operationalized in agricultural systems characterized by biological variability. The ability to quantify non-product output (waste and emissions) in both physical and monetary terms supports the argument that environmental management accounting can function as a strategic control mechanism in primary production sectors.

From Static Accounting to Real-Time Digital Environmental Accounting

A major contribution of this research lies in transforming MFCA from a periodic, static accounting tool into a real-time digital system. Conventional MFCA applications often rely on retrospective data analysis. In contrast, the integration of IoT sensors enables continuous data acquisition, allowing dynamic recalculation of material efficiency and cost flows.

This real-time capability changes managerial behavior (Renaldo & Veronica, 2024). Instead of identifying inefficiencies at the end of an accounting period, farmers receive immediate feedback on feed utilization and environmental conditions. As observed in the improvement of feed efficiency and reduction of material losses, cost transparency directly influences operational decisions.

Thus, the study advances the concept of Digital Environmental Management Accounting (Digital EMA), where accounting is embedded within technological infrastructure rather than functioning as a separate reporting mechanism.

Integrating Emission Accountability within Cost Structures

Sustainability reporting in livestock farming is often treated as an external compliance requirement rather than an internal management tool. By embedding methane (CH_4) and nitrous oxide (N_2O) calculations into the MFCA framework, this study integrates environmental accountability directly into managerial cost analysis.

The discussion reveals that emission data become more actionable when linked to cost flows. Instead of viewing emissions solely as environmental indicators, they are interpreted as manifestations of material inefficiency. This linkage strengthens the economic rationale for sustainability practices.

Therefore, the integration supports the argument that environmental performance and financial performance are not competing objectives but interdependent dimensions of eco-efficiency.

AI as a Complement to Accounting Logic

The inclusion of AI-based decision support enhances predictive capacity but does not replace structured accounting analysis. Rather, AI functions as a complementary layer that improves biological performance while MFCA ensures cost transparency.

This balanced integration avoids a common limitation in smart farming research, where technological sophistication overshadows financial accountability. The study demonstrates that predictive analytics can be embedded within accounting-driven frameworks, ensuring that decisions remain economically grounded.

By linking disease detection and estrus prediction with cost implications, the system aligns biological forecasting with managerial accounting objectives.

Positioning within Environmental Management Accounting Literature

From a theoretical standpoint, this study contributes to the evolution of Environmental Management Accounting in three ways:

- Expanding MFCA application into livestock farming.
- Embedding environmental accounting into digital smart farming systems.
- Demonstrating how eco-efficiency measurement improves real operational outcomes.

The research reinforces the view that accounting innovation can drive technological innovation, rather than merely adapting to it. In this case, MFCA acts as the structural backbone of the smart system, positioning accounting as a central design principle rather than a supplementary feature.

Overall, the findings suggest that positioning MFCA as the analytical core of a smart livestock system creates a new paradigm: accounting-driven smart farming. This paradigm bridges environmental sustainability, cost transparency, and digital innovation, providing a scalable model for sustainable livestock management in emerging economies.

CONCLUSION

Conclusion

This study develops and validates a Material Flow Cost Accounting (MFCA)-Driven Smart Goat Livestock Management System that integrates environmental management accounting, IoT-based monitoring, emission estimation, and AI-driven decision support within a unified digital architecture. The findings demonstrate that positioning MFCA as the analytical core of livestock management enhances cost transparency, improves eco-efficiency, and strengthens sustainability accountability in small- and medium-scale goat farming.

Empirical results indicate measurable improvements in feed efficiency, mortality reduction, cost visibility, emission monitoring, and operational data accuracy. By monetizing material losses and embedding emission calculations into managerial accounting structures, the system transforms environmental performance from a compliance-oriented metric into a strategic economic variable. The integration of AI further enhances predictive capability while maintaining accounting discipline, ensuring that technological decisions remain financially grounded.

From a theoretical perspective, this research extends the application of MFCA beyond conventional manufacturing settings into biological production systems. It introduces the concept of accounting-driven smart farming, where environmental management accounting is embedded within digital infrastructure rather than operating as a separate reporting function. This contributes to the advancement of Digital Environmental Management Accounting (Digital EMA) and demonstrates how accounting innovation can shape technological system design.

From a practical standpoint, the system provides livestock farmers with a real-time eco-efficiency management tool that supports feed optimization, emission tracking, and predictive health management (Arlia et al., 2025). For policymakers and cooperatives, the platform offers structured data for sustainability reporting, traceability, and evidence-based agricultural policy integration.

Despite these contributions, the study is limited by its relatively small sample size and short validation period. Future research should involve multi-site implementation, longitudinal performance assessment, integration of carbon pricing mechanisms, and scalability testing under a Software-as-a-Service (SaaS) model.

In conclusion, this research bridges a critical gap between environmental management accounting and smart agricultural technology. By embedding MFCA within a digital IoT–AI architecture, the study proposes a scalable model for sustainable livestock transformation in emerging economies and positions accounting as a strategic enabler of green technological innovation.

Implication

Theoretical Implications. The findings extend MFCA application from manufacturing contexts to biological livestock systems. This research demonstrates that:

- Livestock farming can be conceptualized as a biological material flow system.
- Real-time IoT data enhances the dynamic application of MFCA.
- Integrating emission estimation into MFCA strengthens environmental cost accountability.
- AI can function as a complementary decision layer without replacing structured accounting logic.

The study contributes to the advancement of Environmental Management Accounting by transforming MFCA from a static cost-allocation tool into a real-time digital management instrument.

Practical Implications. For farmers and cooperatives, the system provides:

- Transparent cost-flow tracking
- Measurable emission reporting
- Predictive health monitoring
- Data-driven feed optimization

For policymakers, the platform supports traceability and sustainability compliance. For accounting scholars, the integration demonstrates a scalable model of digital green accounting.

Implications for Sustainable Livestock Transformation. The discussion suggests that the system contributes to three transformation dimensions:

- Operational Transformation – Improved feed efficiency, reduced mortality, and time savings.
- Managerial Transformation – Shift from expense recording to material-flow-based cost control.
- Sustainability Transformation – Integration of emission tracking within economic decision-making.

This multi-dimensional transformation supports the broader transition toward green agriculture and data-driven livestock industrialization.

Limitations

Despite positive results, several limitations were identified:

- Limited labeled health dataset reduced initial AI model robustness.
- Internet connectivity affected real-time synchronization in rural areas.
- The observation period was relatively short (two months).

Recommendation

Based on the findings of this study, several recommendations are proposed for researchers, practitioners, policymakers, and technology developers to enhance the advancement and scalability of MFCA-driven smart livestock systems.

1. Recommendations for Livestock Practitioners

   Small- and medium-scale goat farmers are encouraged to adopt accounting-integrated digital systems rather than relying solely on operational monitoring technologies. The integration of MFCA within farm management enables real-time identification of material losses, feed inefficiencies, and emission-related costs. Farmers should:

   - Implement structured material flow tracking for feed and waste management.

- Utilize eco-efficiency indicators for decision-making instead of focusing only on revenue metrics.
- Incorporate predictive analytics (AI-based DSS) while maintaining cost-based evaluation frameworks.

Adopting an accounting-driven smart farming approach can enhance both financial sustainability and environmental performance simultaneously.

2. Recommendations for Policymakers and Agricultural Authorities

Government agencies and regional agricultural offices should promote the integration of environmental management accounting within digital livestock transformation programs. Specifically:

- Develop policy incentives for farms that implement emission-tracking and MFCA-based systems.
- Integrate digital livestock accounting platforms with national agricultural databases.
- Support sustainability certification frameworks that incorporate real-time emission and cost transparency data.

Embedding environmental cost accountability at the farm level can strengthen national food security strategies while aligning with climate mitigation commitments.

3. Recommendations for Researchers

Future research should expand the empirical scope and theoretical depth of MFCA application in biological production systems. Suggested research directions include:

- Multi-site and cross-regional validation to test scalability.
- Longitudinal analysis to measure long-term eco-efficiency performance.
- Integration of carbon pricing or environmental taxation scenarios within MFCA valuation models.
- Comparative studies between traditional accounting systems and digital MFCA-based systems.
- Development of structural equation models to empirically test the relationship between MFCA adoption, eco-efficiency, and financial performance.

Further theoretical exploration of Digital Environmental Management Accounting (Digital EMA) is also recommended to strengthen interdisciplinary scholarship between accounting and smart agriculture technologies.

4. Recommendations for Technology Developers and Industry

Technology providers should design smart farming systems that embed structured accounting frameworks as core system components rather than add-on modules. Specifically:

- Develop scalable Software-as-a-Service (SaaS) platforms for livestock eco-efficiency management.
- Enhance AI models with cost-impact simulation features.
- Improve interoperability with government systems and sustainability reporting platforms.

Integrating accounting logic at the system design stage ensures that technological innovation remains economically accountable and environmentally measurable.

5. Strategic Recommendation for Sustainable Livestock Transformation

To achieve sustainable livestock transformation, future initiatives should adopt an accounting-driven smart farming paradigm, where environmental cost accounting, emission monitoring, and predictive analytics operate within an integrated digital ecosystem. This approach aligns operational efficiency with sustainability objectives and strengthens resilience in emerging agricultural economies.

Future Research

Although the findings are promising, the study is limited by a relatively small sample size and short observation period. Biological variability across different breeds and environmental conditions may affect material flow patterns. Future research should:

- Conduct multi-site validation with larger livestock populations.
- Explore longitudinal eco-efficiency measurement.
- Integrate carbon pricing scenarios into MFCA valuation.
- Examine scalability through a Software-as-a-Service (SaaS) model.
- Larger datasets, and long-term cost-performance evaluation.

Such extensions would strengthen the empirical foundation of digital environmental accounting in agriculture.

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REFERENCES

Arlia, Massaguni, M., Ambarwati, E. R., Multazam, A. M., & Renaldo, N. (2025). Community Health Promotion Program: Evaluating the Impact of Health Interventions in the Community. *International Journal of Community Service*, *4*(01), 145–158. https://doi.org/10.55299/ijcs.v4i1.1436

Junaedi, A. T., Suhardjo, S., Andi, A., Putri, N. Y., Hutahuruk, M. B., Renaldo, N., Musa, S., & Cecilia, C. (2024). Use of AI-based Banking Applications for Customer Service. *Luxury: Landscape of Business Administration*, *2*(2), 127–136. https://doi.org/https://doi.org/10.61230/luxury.v2i2.100

Macdonald, K., Bahruddin, Hartoto, A. S., Unger, C., Cisneros, P., Pugley, D. D., Herrera Salazar, D., Winanti, P. S., & Kurniawan, N. I. (2024). The politics of accountability in global sustainable commodity governance: Dilemmas of institutional competition and convergence. *Global Policy*, *15*(5), 838–854. https://doi.org/10.1111/1758-5899.13426

Nassar, F. S. (2026). Strategic role of poultry production sciences in shaping the future of global food security and strengthen sustainability. *Poultry Science*, *105*(5), 106617. https://doi.org/10.1016/J.PSJ.2026.106617

Pence, I., Kumas, K., Siseci Cesmeli, M., & Akyüz, A. (2024). Animal-based CO2, CH4, and N2O emissions analysis: Machine learning predictions by agricultural regions and climate dynamics in varied scenarios. *Computers and Electronics in Agriculture*, *226*, 109423. https://doi.org/10.1016/J.COMPAG.2024.109423

Renaldo, N., Chandra, T., Junaedi, A. T., Panjaitan, H. P., & Jahrizal, J. (2025). A Social Accounting Perspective for Institutional Transformation and Resource Management in the AI-Based Financial Sector. *Jurnal Ekonomi Dan Bisnis Jagaditha*, *12*(2), 230–238. https://doi.org/10.22225/jj.12.2.2025.230-238

Renaldo, N., Fadrul, Andi, Sevendy, T., & Simatupang, H. (2022). The Role of Environmental Accounting in Improving Environmental Performance through CSR Disclosure. *International Conference on Business Management and Accounting (ICOBIMA)*, *1*(1), 17–23. https://doi.org/https://doi.org/10.35145/icobima.v1i1.2743

Renaldo, N., Fransisca, L., Junaedi, A. T., Nyoto, N., Suhardjo, S., Putra, R., Putri, N. Y., Purnama, I., Jahrizal, J., & Yovita, I. (2024). *Etika dalam Membuat Kuisioner bagi Ikatan Cendekiawan Muda Akuntansi*. *4*(2), 101–107.

Renaldo, N., Fransisca, L., Junaedi, A. T., Tanjung, A. R., Chandra, T., Suharti, S., Andi, A., Suhardjo, S., Augustine, Y., & Musa, S. (2024). Real-time Value Creation Metrics in Manufacturing Through Blue Innovation and IoT-Based Accounting. *International Conference on Business Management and Accounting*, *3*(1), 108–118. https://doi.org/10.35145/icobima.v3i1.4903

Renaldo, N., Hafni, L., Hocky, A., Suhardjo, & Junaedi, A. T. (2022). The Influence of Digital Technology and Efficiency Strategy on Business Sustainability with Quality Management as Moderating Variables. *2nd International Conference on Business & Social Sciences*, 1464.

Renaldo, N., Suyono, Andi, Putri, N. Y., & Cecilia. (2023). How Business Intelligence, Intellectual Capital, and Company Performance Increase Company Value? Leverage as Moderation. *Journal of Applied Business and Technology*, *4*(1), 93–99. https://doi.org/https://doi.org/10.35145/jabt.v4i1.123

Renaldo, N., & Veronica, K. (2024). The Role of Artificial Intelligence in Early Detection of Financial Statement Fraud in Digital Financial Institutions, AI-Fraud Behavior Integration Model. *Business Management and Accounting (ICOBIMA)*, *3*(1), 135–144. https://doi.org/10.35145/icobima.v3i1.5093

Said Mohamed, E., Belal, A. A., Kotb Abd-Elmabod, S., El-Shirbeny, M. A., Gad, A., & Zahran, M. B. (2021). Smart farming for improving agricultural management. *The Egyptian Journal of Remote Sensing and Space Science*, *24*(3), 971–981. https://doi.org/10.1016/J.EJRS.2021.08.007

Swalih, M. M., Ram, R., & Tew, E. (2024). Environmental management accounting for strategic decision-making: A systematic literature review. *Business Strategy and the Environment*, *33*(7), 6335–6367. https://doi.org/10.1002/bse.3828

Tran, T. T., & Herzig, C. (2020). Material flow cost accounting in developing countries: A systematic review. In *Sustainability (Switzerland)* (Vol. 12, Number 13). MDPI. https://doi.org/10.3390/su12135413

Usul, H., & Olgun, E. B. (2025). An analysis of material flow cost accounting in companies using different cost accounting systems. *Heliyon*, *11*(4), e42555. https://doi.org/10.1016/J.HELIYON.2025.E42555

Walls, C., Putri, A. R. K., & Beck, G. (2023). Material Flow Cost Accounting as a Resource-Saving Tool for Emerging Recycling Technologies. *Clean Technologies*, *5*(2), 652–674. https://doi.org/10.3390/cleantechnol5020033

Weggeman, M., & Cauffman, L. (2024). Using design science research to develop and validate the application of client-oriented psychological approaches illustrated by the design of a solution-focused approach. *Methods in Psychology*, *11*, 100151. https://doi.org/10.1016/J.METIP.2024.100151

Zhu, L., Yang, X., Xian, Y., Jiang, W., Pu, X., Wang, S., Cheng, J., Niu, L., Zhao, Y., Chen, L., Zhou, X., Wang, Y., Gan, M., Zhu, L., & Shen, L. (2025). Empowering precision livestock farming: Artificial intelligence applications in animal genomic breeding and multi-dimensional phenotypic measurement. *Smart Agricultural Technology*, *12*, 101655. https://doi.org/10.1016/J.ATECH.2025.101655