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Integrating Material Flow Cost Accounting and IoT-Based Monitoring for Eco-Efficient Goat Farm Management

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Abstract
Goat farming plays an important role in supporting rural livelihoods, food production, and agricultural sustainability. However, conventional goat farm management often separates environmental monitoring, financial accounting, and livestock management, limiting the ability to identify resource inefficiencies and associated environmental impacts. This study aims to develop and implement GEMBALA (Green Eco-smart Management-Based Automation for Livestock and Accounting), an integrated digital platform that combines Internet of Things (IoT)-based environmental monitoring, Material Flow Cost Accounting (MFCA), emission analysis, artificial intelligence-based livestock management, and analytical reporting. The research employed a research and development approach in collaboration with CV Cahaya Firdaus (Fathur Farm). An IoT sensor prototype was developed, installed, and tested in a real goat farming environment to monitor temperature, humidity, Heat Index (THI), ammonia gas, and dust density. The platform also incorporates MFCA, emission, AI Estrus, AI Health, and analytical reporting modules. The results demonstrate progress toward integrating environmental, economic, and livestock management information within a unified digital platform. However, further validation is required to improve sensor data transmission, synchronization, emission calculations, MFCA data consistency, and AI performance evaluation. The study provides a foundation for eco-economic decision support, sustainable livestock management, and future commercialization of digital livestock technologies.

Keywords: Goat Farming; Internet of Things (IoT); Material Flow Cost Accounting (MFCA); Sustainable Livestock Management; Environmental Monitoring; Eco-Economic Decision Support; GEMBALA
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1.0 INTRODUCTION

Goat farming plays an important role in supporting rural livelihoods, food production, and agricultural sustainability (Assan N, 2025). However, many goat farms still face challenges in managing production costs, feed resources, environmental conditions, and livestock health. Traditional management practices often separate financial records from environmental monitoring, making it difficult for farmers to understand how material losses and environmental risks affect farm efficiency. Therefore, an integrated digital approach is needed to support more efficient, sustainable, and data-driven goat farm management.

Material Flow Cost Accounting (MFCA) provides a framework for identifying material inputs, outputs, losses, and associated costs (Usul & Olgun, 2025). Meanwhile, Internet of Things (IoT) technology enables real-time monitoring of environmental conditions, including temperature, humidity, heat index, ammonia gas, and dust density. However, the integration of MFCA and IoT in goat farming remains an opportunity for developing a more connected economic and environmental management system. The GEMBALA platform addresses this opportunity by connecting environmental monitoring with economic analysis in a single digital platform.

The disruptive novelty of this research lies in transforming conventional goat farm management from separate monitoring and accounting activities into an integrated eco-economic intelligence system (Renaldo et al., 2023). Instead of treating environmental data and financial information as independent records, the proposed platform connects IoT-based environmental observations with MFCA and emission estimation. This integration is designed to help farmers understand the relationship between resource utilization, material losses, operational costs, and environmental conditions. The approach provides a foundation for more comprehensive decision-making based on both economic and ecological indicators.

This study aims to develop and implement an IoT-based monitoring and MFCA-integrated platform for eco-efficient goat farm management. The system is developed and tested in collaboration with CV Cahaya Firdaus (Fathur Farm), where the sensor prototype is installed and tested in a real livestock environment. The research focuses on system integration, field implementation, and the preparation of a digital platform that can support future development toward scalable and sustainable livestock management.

The novelty of this study is the integration of real-time IoT environmental monitoring and Material Flow Cost Accounting into a unified digital platform for goat farming, enabling the simultaneous observation of environmental conditions, resource-related costs, material losses, and emission indicators. This approach establishes a foundation for eco-economic decision support in livestock management rather than relying solely on conventional production or financial records.

2.0 LITERATURE REVIEW

Material Flow Cost Accounting in Sustainable Agriculture

Material Flow Cost Accounting (MFCA) is an environmental management accounting approach that examines the physical and monetary flows of materials within a production process (Kitada et al., 2022). The method helps organizations identify material losses, resource inefficiencies, and associated costs that may remain hidden in conventional accounting systems. MFCA has been standardized through ISO 14051 and is commonly associated with improving resource efficiency and supporting environmental management decisions. Previous literature indicates that MFCA can support both operational efficiency and strategic decision-making by connecting physical material flows with their financial implications. However, its application has historically been more concentrated in industrial and manufacturing contexts than in agricultural and livestock systems.

In agriculture, MFCA provides an opportunity to assess the relationship between production inputs, material losses, waste, and environmental impacts. A recent study on watermelon farming applied MFCA to identify material, energy, and waste-related costs, demonstrating the potential of the method to connect agricultural resource efficiency with economic and environmental performance. The study also highlighted that conventional cost accounting may not sufficiently represent the economic value of negative outputs, such as production losses and environmental emissions. This suggests that MFCA can be adapted to agricultural systems where feed, water, energy, manure, and other resources influence both production costs and environmental performance.

IoT-Based Monitoring in Smart Livestock Farming

The Internet of Things (IoT) has increasingly been applied in livestock farming to support real-time monitoring, data collection, and automated management (Bhaskaran et al., 2024). IoT-based systems may combine environmental sensors, animal monitoring devices, communication networks, cloud platforms, and web-based dashboards. In sheep and goat farming, existing research has explored the use of sensors and cameras to monitor animal movement, temperature, humidity, carbon dioxide, ammonia, and other environmental parameters. These systems demonstrate the potential of digital technologies to improve livestock monitoring and provide farmers with information for more timely management decisions.

IoT technology is also relevant to goat health and welfare because environmental conditions can influence animal comfort, productivity, and disease risks. A recent review of IoT applications in goat health monitoring discussed the use of wearable sensors, environmental sensors, acoustic monitoring, and machine learning to support the early identification of health-related conditions. However, the effectiveness of an IoT system depends on sensor reliability, data quality (Sudarno et al., 2022), network connectivity, system integration, and field validation. Consequently, the development of a digital livestock platform requires more than installing sensors; it also requires a reliable mechanism for processing, interpreting, and using the collected data.

Digital Technologies for Economic and Environmental Efficiency

Digital agricultural technologies have been increasingly examined for their potential to improve livestock productivity, resource efficiency, and environmental performance (Papadopoulos et al., 2025). A systematic review of digital agricultural technology solutions in livestock farming identified applications related to automated milking, feed and live-weight measurement, and health monitoring. These technologies can support more informed operational decisions, although their economic and environmental benefits depend on the type of technology, farm conditions, implementation quality, and management practices. This literature indicates that digital transformation in livestock farming should be evaluated not only through technological functionality but also through its contribution to operational and sustainability objectives.

Despite this progress, economic accounting and environmental monitoring are often developed as separate functions. IoT systems generally focus on collecting and displaying operational or environmental data, while accounting systems focus on recording financial transactions and production costs. This separation may limit the ability of farmers to identify how material losses and environmental inefficiencies affect economic performance. Recent research on MFCA-based livestock manure management emphasizes the need for integrated frameworks that connect material flows, environmental losses, and financial costs within a unified decision-support structure.

Integration of MFCA and IoT in Goat Farm Management

The integration of MFCA and IoT provides an opportunity to combine real-time operational monitoring with economic and environmental analysis (Sodkomkham et al., 2024) . IoT sensors can generate information regarding environmental conditions, while farm records can provide data on feed use, livestock population, energy consumption, operational costs, and waste management. MFCA can then be used to organize relevant material flows, distinguish positive outputs from material losses, and associate these flows with financial values. This combination may help identify resource inefficiencies that cannot be adequately understood through environmental monitoring or conventional financial accounting alone.

For goat farming, an integrated system could support the analysis of feed utilization, livestock management, environmental conditions, and emission-related indicators. Nevertheless, the integration must be supported by consistent data structures, clearly defined system boundaries, appropriate calculation methods, and validation of sensor measurements. The values generated by an integrated platform should therefore be interpreted according to the observation period, livestock population, input-output data, sensor accuracy, and calculation methodology. This is particularly important when the system is used to support environmental reporting or managerial decision-making.

Research Gap and Disruptive Novelty

Existing studies demonstrate the individual benefits of MFCA for resource and cost analysis and IoT for real-time livestock monitoring (Prayetno, Renaldo, Faruq, et al., 2026). However, the literature also indicates the need for broader applications of MFCA beyond manufacturing and for digital tools that integrate physical, environmental, and financial information. Earlier MFCA research identified limited practical application across different sectors and organizational contexts as an area requiring further investigation. More recent livestock-focused research similarly highlights the importance of integrating economic and environmental dimensions through accessible digital decision-support tools.

This research addresses the identified gap through the development of GEMBALA (Green Eco-smart Management-Based Automation for Livestock and Accounting), a digital platform that integrates IoT-based environmental monitoring with Material Flow Cost Accounting and emission-related analysis for goat farm management. The proposed disruptive novelty is not limited to the use of sensors or digital accounting independently, but lies in connecting environmental observations and resource-related economic information within one management platform. The system is designed to support the identification of environmental conditions, material-related inefficiencies, and associated cost information in a more integrated manner. In this way, GEMBALA provides a foundation for an eco-economic decision-support approach that can be further developed through field validation, improved data integration, and future scalability.

Conceptual Position of the Present Study

Based on the reviewed literature, the present study positions IoT as the data acquisition layer, MFCA as the economic and material-flow analysis framework, and the GEMBALA platform as the integration and decision-support layer. The IoT component collects environmental information from the goat housing environment, while MFCA organizes relevant input-output relationships and identifies potential material losses and associated costs. The web-based platform combines these components with emission analysis, livestock management modules, and analytical reporting. The study therefore focuses on the development and field testing of an integrated digital system rather than claiming the effectiveness of the system solely from its technical availability. Further evaluation of economic efficiency, emission estimates, and AI performance requires validated datasets and documented measurement procedures.

3.0 METHODOLOGY

This study employed a research and development (R&D) approach to develop an integrated digital platform for eco-efficient goat farm management (Prihastomo et al., 2026). The research focused on combining Internet of

Things (IoT)-based environmental monitoring with Material Flow Cost Accounting (MFCA) and emission analysis. The study was conducted in collaboration with CV Cahaya Firdaus (Fathur Farm), which served as the field testing and validation site.

The research consisted of four main stages. First, an IoT-based monitoring system was developed using sensors to measure environmental parameters, including temperature, humidity, heat index (THI), ammonia gas, and dust density. Second, the sensor devices were installed in the goat housing facility and connected to the GEMBALA web platform. Third, the MFCA and emission modules were integrated into the platform to support the analysis of material inputs, operational costs, material losses, and environmental indicators. The platform also included AI-based estrus and health modules, as well as an analytical reporting function.

Finally, field testing was conducted to examine the functionality of the sensor devices and the integration of monitoring data with the web dashboard. The evaluation focused on sensor operation, data transmission, synchronization, and data presentation. The MFCA and emission modules were assessed based on the availability and consistency of operational data. The results were used to identify technical limitations and guide further system improvements. AI performance and emission estimates require additional validation using appropriate datasets, measurement procedures, and reference information before definitive performance conclusions can be drawn.

4.0 RESULTS AND DISCUSSION

Development of the IoT-Based Monitoring System

The research successfully developed and implemented an IoT-based monitoring system for goat housing at CV Cahaya Firdaus (Fathur Farm). The sensor device was manufactured, installed in the partner's goat housing facility, and tested in a real livestock environment. The system was designed to monitor several environmental parameters, including temperature, humidity, Heat Index (THI), ammonia gas, and dust density. The collected information was displayed through the GEMBALA web platform, allowing environmental conditions to be monitored digitally through an integrated dashboard.

The development of the IoT system provides a foundation for improving environmental monitoring in goat farming (Prayetno, Renaldo, Junaedi, et al., 2026). By integrating sensor devices with a web-based platform, farm managers can access environmental information in a more organized manner and identify parameters that require further inspection. However, the integration of data transmission, synchronization, and dashboard presentation still requires further improvement. The reliability of the monitoring system should be evaluated through repeated measurements, sensor verification, and comparison with appropriate reference instruments.

Integration of MFCA and Emission Analysis

The GEMBALA platform has developed MFCA and emission analysis modules to support the integration of economic and environmental information in goat farm management. The MFCA module is designed to analyze material inputs and outputs, feed-related costs, material losses, and operational efficiency. Meanwhile, the emission module supports the estimation and presentation of environmental indicators based on available livestock and operational data.

The integration of MFCA and emission analysis provides an opportunity to connect resource utilization with economic and environmental performance (Nishitani et al., 2022). This approach can help identify potential material losses and support more comprehensive farm management decisions. Nevertheless, the efficiency value of 92.4% and emission value of 84.2 kg CO_2e displayed in the platform should be considered demonstration results until the observation period, livestock population, input-output data, and calculation methods have been fully verified. The zero values displayed for livestock population and MFCA costs also indicate the need for further data entry and dataset configuration before the results can be interpreted as definitive farm performance indicators.

Development of AI-Based Decision Support Modules

The GEMBALA platform includes AI Estrus and AI Health modules designed to support individual goat management. The AI Estrus module provides an interface for selecting individual animals, recording AI diagnosis results, displaying confidence values, and storing information in a reproductive journal. The AI Health module provides a structure for recording physiological parameters, such as body temperature, heart rate, body weight, and physical observations.

The development of these modules demonstrates the potential for integrating artificial intelligence with livestock management and digital recordkeeping (Moe et al., 2025). However, the accuracy of estrus prediction and disease classification has not been conclusively established at this stage. Further evaluation requires labelled datasets, separate training and testing data, and validation against physical observations or reference diagnoses. Therefore, the current results indicate the availability and integration of the AI-DSS interface rather than verified diagnostic accuracy.

Development of the Analytical Reporting Platform

The GEMBALA analytical reporting module has been developed to combine information from IoT monitoring, MFCA, emission analysis, and livestock health monitoring. The interface includes features for selecting livestock units or housing facilities, determining reporting periods, and exporting data to Excel. These functions are intended to support data-based evaluation and improve the accessibility of information for farm managers.

The integration of reporting functions within the platform is important because it allows different categories of farm information to be presented through a single digital system (Gebresenbet et al., 2023). This supports the research objective of connecting environmental monitoring with economic and livestock management information. However, the usefulness of the reporting module depends on the completeness, consistency, and accuracy of the data entered into the system. Further validation is required to ensure that the reports accurately reflect field conditions and the underlying MFCA and emission calculations.

Field Implementation and Research Contributions

The implementation at Fathur Farm demonstrates the transition of GEMBALA from system development toward field testing and potential commercialization. The partner contributed through the provision of the goat housing location, livestock for testing, operational support, and assistance during sensor installation and testing. The implementation enabled the research team to examine the system under real livestock farming conditions and identify technical requirements for further development.

The main contribution of this research is the integration of IoT-based environmental monitoring with MFCA, emission analysis, AI-based livestock management, and analytical reporting within a single platform. This integrated approach creates a foundation for eco-economic livestock management by connecting environmental observations with operational and cost-related information. Nevertheless, claims regarding improved farm efficiency, emission reduction, AI accuracy, and large-scale operational readiness require additional quantitative evidence and systematic validation.

Discussion of Technical Challenges and Future Improvements

The main technical challenge identified during the research was the integration of the IoT sensor devices with the GEMBALA web dashboard. Although the sensors had been developed, installed, and tested, the transmission, synchronization, and presentation of sensor data still required improvement. These challenges were associated with hardware configuration, system programming, data validation, and coordination of testing activities with the operational conditions of the partner's goat housing facility.

To address these challenges, further development should use a staged testing process involving sensor measurement, data transmission, server processing, data storage, and dashboard visualization. Each stage should be documented and tested separately before full system integration. Additional validation should also be conducted for the MFCA and emission modules by ensuring consistent livestock population data, feed information, operational records, and calculation procedures. This process is expected to improve system reliability and support the preparation of the GEMBALA platform for further development and commercialization.

Overall Discussion

Overall, the research has produced an integrated GEMBALA prototype consisting of IoT monitoring, MFCA and emission analysis, AI-based estrus and health modules, and analytical reporting. The prototype has been implemented and tested at the partner's goat farm, representing progress from initial system development toward field application. The results support the feasibility of integrating economic, environmental, and livestock management information into one digital platform.

The disruptive potential of the research lies in the integration of environmental monitoring and economic accounting rather than the independent use of IoT or MFCA. However, the novelty and practical impact of the platform should be demonstrated through additional field data, comparison with conventional management practices, verification of calculation methods, and quantitative evaluation of system performance. The current findings therefore provide a foundation for further technical refinement, validation, intellectual property development, and future commercialization of GEMBALA.

5.0 CONCLUSION

Conclusion

This study developed and implemented the GEMBALA platform (Green Eco-smart Management-Based Automation for Livestock and Accounting) to support eco-economic goat farm management through the integration of IoT-based environmental monitoring, Material Flow Cost Accounting (MFCA), emission analysis, AI-based livestock management, and analytical reporting. The IoT sensor prototype was manufactured, installed, and tested at CV Cahaya Firdaus (Fathur Farm). The platform provides monitoring functions for temperature, humidity, Heat Index (THI), ammonia gas, and dust density, as well as MFCA, emission, AI Estrus, AI Health, and reporting modules. These results demonstrate progress toward an integrated digital livestock management platform. However, further validation is required to verify sensor accuracy, data consistency, emission calculations, and AI performance before the system can be considered fully validated for large-scale implementation.

Implications

This research has practical implications for livestock farmers, researchers, and technology developers. The integration of IoT and MFCA provides a foundation for connecting environmental monitoring with economic and operational information in goat farming. The GEMBALA platform can support more structured data collection, monitoring of housing conditions, identification of potential resource losses, and preparation of analytical reports. For farmers, the platform may improve access to information for management evaluation, while for researchers, it provides a basis for further investigation into sustainable livestock production, environmental accounting (Renaldo et al., 2022), and digital decision-support systems. The practical benefits of the platform should be assessed through further field validation and measurable performance evaluation.

Limitations

The main limitation of this study is the technical integration between the IoT sensor devices and the GEMBALA web dashboard. Although the sensors have been developed, installed, and tested, data transmission, synchronization, and dashboard presentation still require further improvement. The MFCA and emission analysis modules also require more complete and validated data, including livestock population, observation periods, material inputs and outputs, operational costs, and calculation parameters. In addition, the accuracy of the AI Estrus and AI Health modules has not yet been conclusively established because further labelled datasets and validation against reference observations or diagnoses are required. The current study therefore demonstrates prototype development and field implementation rather than definitive evidence of improved farm efficiency, emission reduction, or AI diagnostic accuracy.

Recommendations

Further development should prioritize the improvement of IoT connectivity, data transmission, server synchronization, and dashboard visualization. System testing should be conducted incrementally, beginning with sensor measurement and continuing through data transmission, server processing, data storage, and dashboard presentation. The research team should also complete the prototype documentation, testing records, and technical validation documents to support the patent and other intellectual property outputs. The MFCA and emission modules should be supported by consistent operational data and clearly documented calculation procedures. For the AI modules, the development team should prepare labelled datasets, establish training and testing procedures, and conduct validation using appropriate reference data. Collaboration with Fathur Farm should be maintained to support field testing and the refinement of the platform based on practical livestock management requirements.

Future Research

Future research should focus on improving the scalability, reliability, and commercialization readiness of the GEMBALA platform. The next development stage may include the transformation of the platform into a Software as a Service (SaaS) model, the development of Android and iOS mobile applications, integration of digital payment services, and expansion to other livestock commodities. Further research should also examine the use of advanced AI for livestock health, reproduction, productivity, and environmental analysis. The platform may subsequently be evaluated for integration with relevant government systems and potential international application. These developments should be supported by long-term field datasets, comparative testing, economic evaluation, environmental performance analysis, and validation across different livestock management conditions. The research roadmap should remain aligned with the readiness of the technology, partner availability, validation results, and available funding.

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