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INTELLIGENT SYSTEM FOR SUSTAINABLE BEEF CATTLE FARM MANAGEMENT FOR GHG AND AP REDUCTION

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Abstract

Livestock farming is a vital component of global food production, supplying essential resources such as meat and dairy. However, it is also a major contributor to environmental challenges, particularly greenhouse gas (GHG) and atmospheric pollutant emissions. The beef cattle sector is responsible for significant methane (CH_4) and nitrous oxide (N_2O) emissions due to enteric fermentation and manure management. Additionally, inefficient resource utilization and suboptimal farm practices exacerbate environmental degradation and economic losses. As global demand for livestock products grows, there is an urgent need to adopt sustainable farming practices that optimize production while minimizing ecological impact. We propose an innovative approach to sustainable livestock farming by integrating Internet of Things (IoT), blockchain, and artificial intelligence (AI) technologies. IoT sensors will monitor critical environmental and livestock parameters, The collected data is securely stored and managed using blockchain technology, ensuring transparency, traceability, and stakeholder trust. AI-driven models analyse input data to optimize feeding practices, manure management, and overall farm productivity. These technologies will form the backbone of a decision-support system designed to enable farmers to reduce emissions while improving operational efficiency.

Key words: *blockchain, greenhouse gas emissions, IoT, livestock management, sustainability.*

INTRODUCTION

Livestock farming plays a significant role in global food production, providing essential resources such as meat, dairy, and by-products that sustain populations worldwide. However, the industry is also a significant contributor to environmental challenges, particularly through greenhouse gas (GHG) emissions. The beef cattle sector, in particular, is associated with high methane (CH_4) and nitrous oxide (N_2O) emissions, primarily due to enteric fermentation and manure management processes. Additionally, inefficient resource utilization, high water consumption, and suboptimal farm management practices contribute to economic losses and increased environmental degradation. As global demand for livestock products continues to rise, the need for more sustainable farming practices becomes increasingly urgent (Davidescu et al., 2023).

In recent years, the adoption of smart farming technologies has gained attention as a potential solution to enhance sustainability in livestock production. The integration of Internet of Things (IoT) sensors, artificial intelligence (AI), and blockchain technology presents new opportunities for optimizing farm operations, improving animal welfare, and reducing emissions. IoT-enabled monitoring systems allow real-time data collection on environmental conditions and animal health, facilitating precise management interventions. AI-driven analytics provide insights for precision feeding, waste management, and predictive decision-making, enabling more efficient resource allocation and reducing emissions at the source. Meanwhile, blockchain technology ensures transparency, traceability, and secure data sharing among stakeholders, fostering trust and compliance with sustainability standards.

The transition toward smart, data-driven livestock management has the potential to revolutionize traditional farming practices. By integrating these advanced technologies, farms can optimize production while minimizing their ecological footprint. However, the effective implementation of such systems requires careful planning, testing, and validation to ensure their scalability and adaptability to real-world farming conditions.

In this context, the paper presents the development and implementation of a smart management system for beef cattle farms, designed to minimize GHG emissions while enhancing farm productivity. The study evaluates the impact of advanced monitoring technologies on emission reduction and sustainable livestock production, contributing to climate change mitigation and efficient resource management.

MATERIALS AND METHODS

The management of beef cattle production involves a significant number of variables, and their interaction and combination to optimize the process present continuous challenges. Increasing the precision and accuracy of decision-making in beef production can be achieved through mechanisms that influence growth rate (age at slaughter and average daily gain), as well as animal nutrition, pasture management, etc. (D'Aurea et al., 2021). These factors can significantly contribute to reducing greenhouse gas (GHG) emissions and air pollutants. The innovative aspect of this proposal, in the context of reducing GHG emissions and air pollutants while improving sustainability, lies in the comprehensive integration and application of IoT and blockchain technologies tailored to the specific needs of this sector.

Although IoT monitoring has been implemented in agriculture and livestock farming (Parisa Niloofar et al., 2021), its application for the sustainable optimization of beef cattle farms, with a focus on reducing GHG emissions and air pollutants, represents an innovative approach. The use of sensors for real-time monitoring of environmental conditions, animal health and behaviour, and resource utilization efficiency enables precise management adapted to the individual needs of animals and farms, but it requires specific techniques (Emi Mwaka Katemboh et al, 2020). By implementing an innovative monitoring system for feed quality parameters in beef cattle farms (Džermeikaitė et al, 2023), farmers could have a more efficient resource for adjusting rations to reduce GHG emissions at the ruminal level, as well as a more effective farm management strategy to maximize production performance and animal health while simultaneously decreasing air pollutants and GHG emissions from manure management (Panchasara et al., 2021).

The integration of blockchain technology in data management and the beef cattle supply chain is also an innovative aspect (Hancock, 2019). It provides a level of transparency, security, and efficiency in data sharing and transactions that has not yet been fully explored in this sector. The use of smart contracts to facilitate fairer commercial agreements and reward sustainable practices adds a new dimension, encouraging the adoption of low-GHG-emission practices.

At both national and international levels, there are initiatives that address individual components of this proposal, such as the use of IoT technology for animal monitoring or the application of blockchain for supply chain traceability (Nóbrega et al., 2018). However, integrating these components into a complete system that specifically addresses GHG and air pollutant emission reduction in beef cattle farms, efficiency and sustainability improvements, and the creation of a knowledge-sharing and education framework is unique. This represents a significant step forward, due to the use of a multi-criteria analysis of inputs and outputs within the bioeconomic beef cattle farm system.

RESULTS AND DISCUSSIONS

Proposed architecture

In order to characterize the potential impact of advanced technologies on the sustainability of beef cattle farming, this study proposes the development and implementation of an integrated system that combines Internet of

Things (IoT), artificial intelligence (AI), and blockchain technology. These components will work together to create a smart livestock management system aimed at optimizing farm efficiency, improving animal welfare, and reducing environmental impact.

The system is designed to assess key sustainability indicators, including greenhouse gas (GHG) emissions reduction, environmental parameters such as air quality, temperature, humidity, methane (CH_4), and ammonia (NH_3) levels, as well as animal health, productivity, and resource utilization efficiency. IoT sensors will be deployed throughout the farm to continuously monitor these parameters, transmitting high-frequency data to a centralized database for real-time analysis. The system will detect anomalies, such as sudden spikes in methane emissions or deviations in air quality, allowing farm operators to make immediate adjustments.

The resulting solution will be an intelligent system (Figure 1) that relies on an existing software platform for traceability and certification of livestock products from low-greenhouse gas (GHG) emission farms and will use advanced solutions for modelling the management of GHG emissions and air pollutants.

Structurally, the system's architecture is based on a series of software components associated with data flows and technological models for managing GHG emissions and air pollutants, as follows:

- **IoT sensor system** that measures a wide range of parameters in livestock farms, particularly microclimate conditions: temperature, humidity, pressure, CO_2, N_2O, NO_2, NH_3, CH_4, VOCs, PM_{10}, $PM_{2.5}$, PM_1.
- **Multi-protocol gateway (LoRaWAN, 4G/5G)** ensuring redundant connectivity.
- **Complex database** capable of collecting data in any format (structured or unstructured).
- **Blockchain-based system** that enables data traceability and provides different levels of access for stakeholders interested in certifying products from farms with reduced GHG and/or air pollutant emissions.
- **Machine learning algorithms** that facilitate the development of an intelligent model for managing GHG and air pollutant emissions.
- **Intelligent emission management model** that, based on input data (nutritional parameters of feed, technological parameters, microclimate parameters, and energy parameters), utilizes machine learning to determine output variables (average daily gain, GHG and air pollutant emissions, production parameters, etc.) while also allowing control of certain farm parameters (nutritional or technological parameters).
- **Application Programming Interfaces (APIs)** that enable access to the system, both for its internal components and for its internal components and for other potential entities (third-party software developers, authorities, etc.).
- **User interface** that supports both product traceability and farm management.

Implementation and preliminary results

The diagram in Figure 1 outlines a multi-tiered structure, beginning with IoT sensors deployed to collect critical farm data, including environmental parameters, animal health metrics, and feed quality.

The data flow begins by acquiring data (monitoring) of physical parameters configured in the system such as: methane emissions, certain gases (such as NOx, CO_2, CH_4, NH_3 etc.), temperature, humidity etc., this monitoring being carried out using sensors. The information is collected and stored integrated at the middleware level (consisting of an MQTT broker, Telegraf and InfluxDB software).

Also at this level, the blockchain system has a very important role because it manages to ensure data traceability, data protection, data sharing and smart contracts. The blockchain system collects data coming from the middleware through a server placed on top of the Hyperledger Fabric framework. The server offers a series of API interfaces for interaction with the blockchain system, both for registering transactions in the ledger and for executing smart contracts

A script written in Python ensures the extraction of data from the InfluxDB database (which integrates sensor data received via MQTT) and its introduction into the blockchain system through the API interface provided by the server.
At the same time, a client application written in NodeJS allows the user (farmers or other agricultural stakeholders) to interact with the system *without the need for technical knowledge*. The client application (Figure 2) hides the technical complexity for users, but as the server also provides API interfaces, any other potentially interested actors (e.g. third-party developers) can connect to the system and develop new products and services.

Example smart contract execution - updating the NH_3 emission value

In order to execute a smart contract - updating the NH_3 emission value, we permanently ran a Python script through which values are taken from Influx and recorded as transactions in the blockchain system. When detecting an NH_3 value higher than the previous one, the script updates the value of the NH_3 field of each animal belonging to the respective farm. Thus, the script will take this value and update (by executing the smart contract) the NH_3 value of all animals on the farm. Figure 3 illustrates one of the ANIMAL type entities viewed through the front-end application.

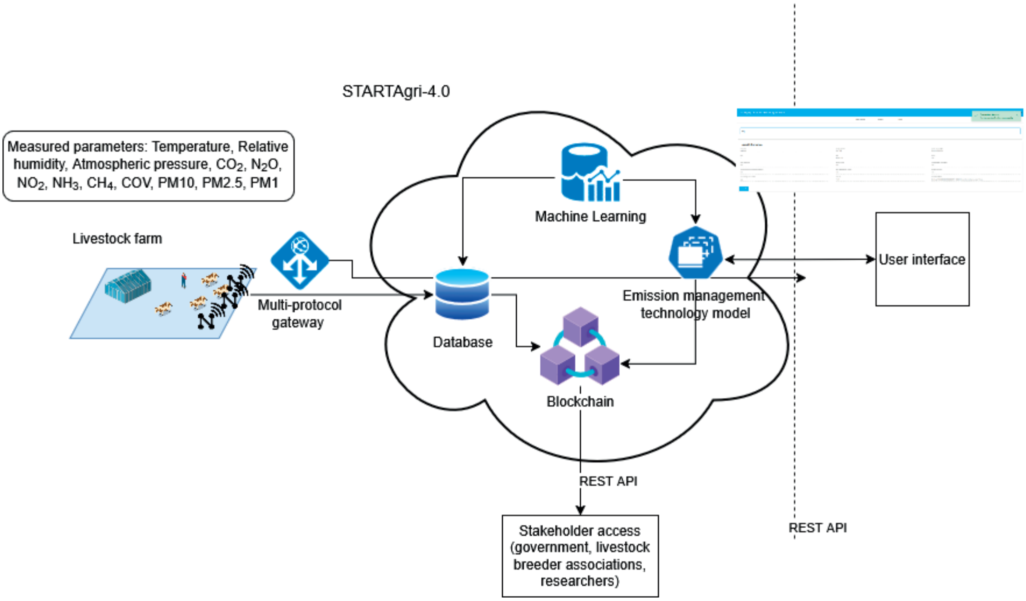
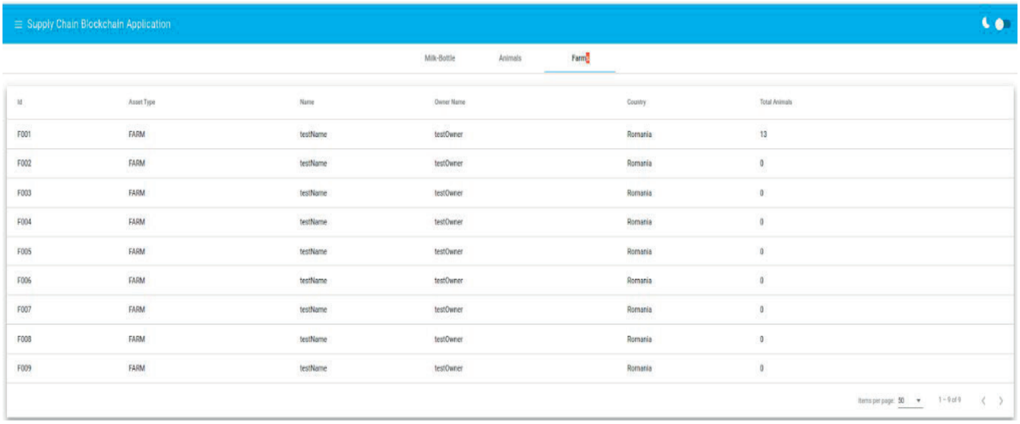


Figure 1. Diagram of the connection of the STARTAgri-4.0 system components



Id	Asset Type	Name	Owner Name	Country	Total Animals
F001	FARM	testName	testOwner	Romania	13
F002	FARM	testName	testOwner	Romania	0
F003	FARM	testName	testOwner	Romania	0
F004	FARM	testName	testOwner	Romania	0
F005	FARM	testName	testOwner	Romania	0
F006	FARM	testName	testOwner	Romania	0
F007	FARM	testName	testOwner	Romania	0
F008	FARM	testName	testOwner	Romania	0
F009	FARM	testName	testOwner	Romania	0

Figure 2. Client application - querying the blockchain system for listing all FARM entities

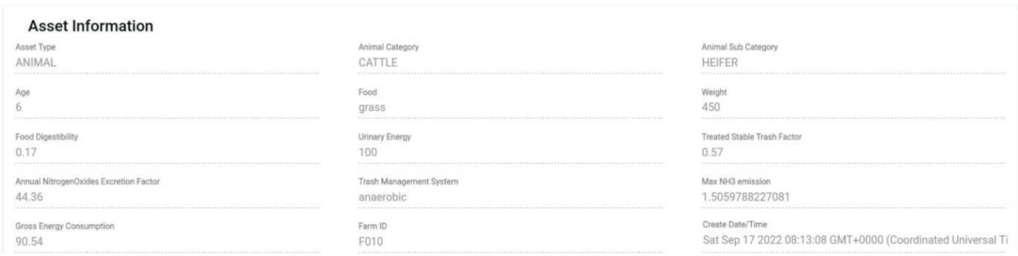


Figure 3. Displaying the ANIMAL asset entry with the updated NH_3 parameter value

Pilot implementation considerations

The pilot implementation of the STARTAgri-4.0 system will focus on testing its functionality and scalability in selected beef cattle farms. Key performance indicators such as GHG emissions, resource utilization, and animal health metrics will be monitored to assess the effectiveness of the proposed solutions.

AI-driven decision-making

The integration of AI-driven decision-making in livestock farm management presents both opportunities and challenges. AI algorithms can analyse vast amounts of sensor data in real time, enabling predictive analytics for optimizing animal health, feed efficiency, and environmental impact. It can identify patterns in methane emissions, resource consumption, and animal behaviour, leading to more precise interventions that enhance farm sustainability. However, the reliability and transparency of AI-generated decisions are extremely important, requiring validation mechanisms and interpretability to ensure trust among farmers and stakeholders. Additionally, the integration of AI must consider ethical concerns, data privacy, and the adaptability of models to diverse farm conditions. The successful implementation of AI-driven decision-making in GHG emission reduction strategies will depend on the balance between automation, human oversight, and the ability to refine models based on real-world feedback.

CONCLUSIONS

In this research it was proposed an innovative approach to addressing the environmental and operational challenges in livestock farming by integrating IoT, AI, and blockchain technologies into a unified system. By focusing on real-time monitoring, secure data management, and AI-driven decision-making, the project aims to enhance sustainability and operational efficiency in beef cattle farming.

The proposed system architecture, which includes IoT sensors for data collection, AI algorithms for predictive analytics, and blockchain for data integrity and traceability, represents a significant step forward in the adoption of smart farming practices. These technologies will enable precision feeding strategies to reduce methane emissions, advanced waste management to minimize ammonia levels, and transparent data management to ensure compliance with sustainability standards.

Pilot testing of the system in selected farms will validate its functionality, scalability, and impact on key sustainability indicators, including greenhouse gas emissions, resource utilization, and animal health.

The STARTAgri project reflects a comprehensive and forward-looking approach to sustainable agriculture. By using advanced digital technologies, it has the potential to transform traditional farming practices into intelligent and environmentally responsible systems. The results of this initiative have the potential to contribute to global efforts in climate change mitigation, setting a benchmark for the integration of smart technologies in agriculture and paving the way for future advancements in sustainable livestock farming.

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