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# An Ontology-Driven Framework for Animal Traceability in Botswana

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## Abstract

This study developed an ontology-driven framework for animal traceability (ODF-AT) in Botswana, aiming to enhance interoperability, integration, and standardization among stakeholders in the livestock sector. The framework addresses challenges in disease monitoring, theft prevention, and compliance with international trade standards. A mixed-methods approach was employed, utilizing qualitative and quantitative data collection through interviews, structured questionnaires, and project mapping with NVivo software. Stakeholders, including farmers, veterinary professionals, government officials, and Botswana Meat Commission representatives, provided insights into current practices and traceability challenges. The ODF-AT consists of four layers: input, semantic core, knowledge management, and application. It integrates technologies like ontology-based knowledge management and sensor devices, enabling real-time data capture, secure processing, and user-friendly interfaces. Results show that the ODF-AT improves data exchange and communication among stakeholders, offering a scalable and reliable system for livestock management. Although the framework shows promise, further research is needed to adapt it for other regions, overcome practical implementation challenges, and validate its effectiveness through pilot projects.

## Keywords

Animal traceability, ontology-driven framework, interoperability, livestock management, food safety, disease control.

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## Introduction

Effective traceability systems are essential for ensuring food safety and quality, addressing growing consumer concerns about the authenticity and origin of animal products. The ability to trace the movement of animals and their related products is key to success in animal disease control (Salina et al., 2021). Effective traceability not only meets consumer demands for transparency and safety but also strengthens compliance with international trade regulations, opening up access to premium markets that value both animal welfare and traceability (Nkatekho, 2024). Technologies such as RFID, DNA fingerprinting, and chemical component fingerprinting provide critical tools for individual animal identification and meat product traceability, significantly reducing food fraud risks and enhancing transparency across the supply chain (Zhao et al., 2020). Traceability, alongside attributes like animal welfare and place of origin, enhances consumer trust and satisfaction, thus fostering a safer food supply chain (Chen et al., 2021). The study by Tran et al. (2024) indicates that consumer willingness to pay (WTP) for traceable meat products is significantly higher than for other food categories, highlighting the increasing demand for transparency and safety in animal-derived food products. Additionally, the integration of traceability with other credence attributes, such as organic or animal welfare certifications, further elevates consumer WTP, underscoring the value of a comprehensive traceability system that aligns with consumer preferences and expectations (Tran et al., 2024). The study by Bowling et al. (2008) highlights the use of various devices for animal traceability, such as RFID tags and rumen boluses, across different countries, as well as the challenges associated with information management. Current animal traceability systems face challenges such as the lack of interoperability and integration across different technologies and platforms. This lack of interoperability contributes to heterogeneous business models and ineffective data and knowledge management, which complicates the tracking and management of animals across supply chains (Addo-Tenkorang et al., 2019). The interoperability challenges due to varied technological solutions and standards used by different stakeholders impede seamless traceability across the supply chain (Füzesi et al., 2010).

### Challenges in animal traceability in Botswana

In Botswana, the livestock sector plays a critical role in the economy, contributing significantly to food security, employment, and rural development, with beef being the only contributor to foreign exchange earnings from the livestock sector (Bahta et al., 2023). Substantial resources and budget have been allocated to safeguarding the livestock industry, reflecting its critical role in foreign exchange earnings, food security, and the livelihoods of a large segment of the population, while addressing challenges such as productivity stagnation and market exploitation (Van Engelen et al., 2013). The European Union's export requirements mandate stringent monitoring of animal diseases and traceability from farm to fork (European Commission, 2019; European Commission, 2024).

The first animal traceability system introduced in Botswana in 2001 was the Livestock Identification Trace-back System (LITS) (Bowling et al., 2008; Oladele & Jood, 2010). LITS in Botswana utilized RFID technology to electronically tag and track cattle, linking each animal to a central database that recorded its identity, ownership, health status, and location. LITS aimed to enhance cattle traceability, support disease monitoring, and meet European Union export requirements, thereby facilitating access to lucrative international markets and promoting better livestock management practices. Currently, the animal traceability system used in Botswana is the Botswana Animal Identification and Traceability System (BAITS). BAITS serves as a comprehensive platform enabling farmers to systematically record information related to their livestock. It facilitates critical functions such as animal registration, transfer of ownership, tracking the arrival of livestock, documentation of veterinary drug treatments, and reporting the removal of deceased or slaughtered animals. Accessible online, BAITS allows for reporting livestock losses, whether due to natural causes or slaughter, thereby enhancing traceability and management within the livestock sector (Government of Botswana, 2022).

### An overview of animal traceability technologies

The paper by Resti et al. (2024) discusses various technologies used in dairy recording tools, including mobile phone applications, desktop applications, web applications, networks, and the Internet of Things (IoT). Mobile phone applications are identified as the most widely used due to their accessibility and ease of use, especially in regions with limited infrastructure. IoT has the potential to automate data collection and provide real-time information, enhancing farm management efficiency. The integration of IoT with other technologies, such as networks and mobile apps, is mentioned as a way to improve the user-friendliness and effectiveness of dairy recording tools. However, challenges related to Internet connectivity and the need for continuous data input are acknowledged as critical factors influencing the successful implementation of these technologies in developing countries.

Pereira et al. (2023) identified various RFID-based methods used for livestock management, animal tracking, traceability, and animal behavior monitoring. Passive UHF RFID tags are the most common, due to their cost-effectiveness and ease of use in tracking cattle and other mammals. RFID is often integrated with other technologies like GPS and cameras to enhance tracking accuracy and provide real-time location data, which is particularly valuable for monitoring animal movement and behavior in large or remote areas. Other integrations include infrared sensors and wireless sensor networks, which help gather additional health and environmental data, facilitating comprehensive monitoring systems. The paper does not propose any new animal traceability technologies but instead reviews the existing methods and their applications in different animal tracking scenarios.

A review paper by Zanetoni et al. (2024) investigates the potential application of blockchain technology in animal product traceability systems, highlighting its emerging role in ensuring food safety and quality. Zanetoni et al. (2024) emphasize that blockchain can provide a decentralized, secure, and transparent method of recording and sharing data across the entire production chain, from farm to consumer. By doing so, blockchain addresses key concerns such as traceability, transparency, and consumer trust, which are increasingly important in food supply chains. The review identifies various use cases where blockchain has been implemented or proposed, such as in the tracking of beef, milk, eggs, fish, and pork, showing its versatility across different types of animal products. However, this review paper does not propose any new blockchain technologies; rather, it compiles existing knowledge and examples from the literature to illustrate the benefits and challenges associated with adopting blockchain for animal traceability.

Hernandez San Juan and González-Vaqué (2020) suggest the use of blockchain technology for enhancing animal traceability within the food supply chain by providing a secure and transparent way to record and verify each step in the production and distribution processes. Blockchain's decentralized ledger system ensures that data related to animal origins, health records, and movement is tamper-proof and easily accessible to all stakeholders, thus improving food safety and quality control. By enabling real-time tracking of animals from farm to fork, blockchain helps meet regulatory requirementsand consumer demands for transparency in the supply chain. The technology's capacity to create a permanent and verifiable record of transactions makes it a reliable tool for preventing fraud and ensuring compliance with food safety standards. Overall, blockchain offers an efficient, scalable, and trustworthy solution for enhancing traceability and accountability in the animal agriculture sector.

García-Infante et al. (2024) investigated the effectiveness of machine learning algorithms as tools for meat traceability, specifically to classify Spanish Mediterranean lamb carcasses based on production systems. The study evaluated six different algorithms, namely, artificial neural networks (ANNs), decision trees, k-nearest neighbors (KNN), naive Bayes, multinomial logistic regression, and support vector machine (SVM), using datasets that include organoleptic, sensory, and nutritional traits of lamb meat. The ANN and SVM algorithms demonstrated the highest accuracy in categorizing lamb production systems, with ANN achieving accuracy scores of up to 0.88. In contrast, the KNN algorithm showed the lowest performance, with accuracy scores of 0.54 or lower. The study highlights the potential of machine learning tools to enhance the traceability and classification of meat products, suggesting that their use can improve transparency and consumer confidence in the meat industry. Using machine learning algorithms to enhance meat traceability aligns with our research's goal of improving animal traceability systems, by demonstrating the importance of advanced technological tools for ensuring food safety, quality, and consumer trust.

Gbashi and Njobeh (2024) explored the potential application of artificial intelligence (AI) and machine learning (ML) for enhancing food integrity and, specifically, animal traceability. The authors examine how AI and ML can automate and improve the accuracy of tracking and monitoring livestock movements, health status, and environmental conditions. The review highlights various AI and ML techniques, such as predictive analytics, image recognition, and anomaly detection, that could optimize data collection and decision-making processes in animal traceability. The paper also discusses the integration of these technologies with existing systems to enhance data management, provide real-time insights, and improve food safety and disease outbreak response. do not develop any new technologies for animal traceability based on AI and ML; instead, they focus on reviewing existing research.

Navia et al. (2024) reviewed various sensor technologies used for monitoring the vital signs of livestock, emphasizing applications that enhance animal health and welfare. The study identified long-range communication technologies such as LoRaWAN as the most common for transmitting data from sensors monitoring parameters like movement, geo-location, body temperature, and heart rate. Short-range technologies like Bluetooth and WiFi are also used, often in combination with long-range systems for better coverage. The paper suggests opportunities for developing more comprehensive sensor solutions that enhance traceability by providing continuous location data and robust communication capabilities. It also emphasizes the need for integrating energy-harvesting technologies to improve the autonomy and sustainability of these traceability systems.

León et al. (2024) evaluated the effectiveness of handheld near-infrared spectroscopy (NIRS) as a non-destructive tool for traceability and authentication of the aging process in Angus beef steaks. Using partial least squares-discriminant analysis, the study demonstrates high accuracy in distinguishing between aged and non-aged beef and predicting refrigeration storage times, with over 90% accuracy in external validation. This research suggests that NIRS technology could be valuable in digital transformation strategies for meat supply chain traceability, ensuring product authenticity and enhancing consumer trust. The paper highlights the importance of advanced, non-destructive technologies for ensuring authenticity and enhancing traceability, which aligns with our goal of developing interoperable and standardized traceability systems for the livestock sector.

### Animal traceability frameworks

Füzesi et al. (2010) proposed a framework for animal traceability. The study introduces the concept of a digital business ecosystem (DBE) as a potential solution to improve traceability and information exchange in the meat industry. The DBE framework is designed to create an Internet-based environment where businesses can efficiently interact, share data, and implement traceability methods. This approach emphasizes using modern technologies like barcodes, RFID, and XML-based data sharing to ensure continuous and reliable traceability across different stages of the meat production and supply chain. The DBE framework aims to address interoperability challenges and promote standardized practices, which are essential for effective animal traceability.

The framework for animal traceability by Bai et al. (2017) is structured around key components, including the identification of traceable resource units (TRUs), a centralized database to store and manage data related to these TRUs, and an information flow mechanism that facilitates the collection, processing, and inquiry of traceability information. The framework aims to ensure effective tracking of animals from their origin to the final product, enhancing transparency and compliance with health and safety regulations.

Marinello et al. (2017) presented a framework for a traceability system specifically designed for the animal product supply chain using blockchain technology. This framework aims to enhance the transparency, security, and efficiency of tracking animal products from their origin to the end consumer. By utilizing blockchain's decentralized and immutable nature, the proposed framework ensures that data related to animal health, feed, and movement is securely recorded and easily accessible by all stakeholders in the supply chain, including farmers, regulators, and consumers. This approach is intended to improve food safety, comply with regulatory requirements, and increase consumer trust by providing verifiable and tamper-proof information.

Addo-Tenkorang et al. (2019) proposed a conceptual framework for advanced animal traceability using Internet of Things (IoT) technologies to enhance supply chain management. The framework integrates RFID technology, solar-powered electronic tags, GPRS, GSM, and Google Earth to track animal health, birth records, ownership history, and location. By employing a cloud-based architecture, the framework aims to provide a low-cost solution for farmers, addressing vulnerabilities such as stock theft, straying animals, and inadequate health management. This IoT-driven approach promises to improve visibility and data transmission across the supply chain, contributing to better management practices in animal husbandry. The proposed system highlights the potential for digitization to add value to agricultural businesses, especially in free-ranging environments in Africa.

Chen et al. (2019) presented a mobile solution for pork traceability using 2D barcode technology, focusing on improving food safety and quality in China's pork supply chain. The system enables the collection, transformation, and delivery of traceability information from breeding to retail, integrating seamlessly with government supervision systems. It offers a cost-effective alternative to RFID by utilizing batch-based traceability rather than individual animal tagging, making it accessible for smaller-scale operations common in China. The implementation in Jilin Province demonstrated enhanced transparency and credibility of pork traceability, promoting consumer confidence and regulatory compliance. This approach is relevant to our research on animal traceability technologies as it illustrates the successful application of mobile and barcode technologies to create an effective and scalable traceability system.

A framework for animal identification and traceability using AI-based muzzle recognition technology utilizes deep learning algorithms and convolutional neural networks to analyze unique muzzle patterns of bovine animals, providing an accurate and cost-effective alternative to traditional methods like ear tags (Girish et al., 2020). Key components of the framework include muzzle detection, face alignment, feature extraction, and pattern recognition, which collectively enable the precise identification of animals. The system integrates a mobile application interface for capturing and uploading images, along with a MySQL database to store image links and identification numbers, ensuring efficient data management and verification. By leveraging open-source technologies and ensuring cross-browser compatibility, the proposed framework offers a scalable and field-friendly solution for enhancing animal traceability in various applications such as farm management, disease control, and livestock insurance.

A "butcher-to-farm" traceability framework designed for smallholder pig systems in Western Kenya aims to enhance disease control, food safety, and production efficiency (Mutua et al., 2020). This framework integrates the use of coded plastic ear tags to uniquely identify pigs, with records of pig movements, health events, and sales maintained by farmers, traders, and slaughterhouse operators. The system integrates data capture and database management technologies to ensure accurate tracking from the farm through to the slaughterhouse and butcher shops. It emphasizes the importance of involving local veterinary authorities and stakeholders to implement and maintain the system effectively. The traceability framework is intended to facilitate early detection and containment of diseases like African swine fever and cysticercosis, thereby improving public health and potentially opening new market opportunities for smallholder farmers.

A conceptual framework for animal traceability, suggested by Mwanga et al. (2020) as a result of a literature review, integrates various components, including electronic record-keeping, RFID technology, and mobile devices, to track and manage livestock data effectively. It involves a centralized system that allows data collection at the farm level, which is then transmitted to local and national databases for comprehensive tracking. RFID tags and sensors are used to monitor animal movements, health, and other critical information, enhancing traceability from farm to fork. The framework also incorporates mobile applications for farmers to input and access data easily, facilitating real-time decision-making and compliance with international traceability standards. This integrated approach aims to improve disease control, food safety, and marketability of livestock products by ensuring accurate and reliable animal identification and record-keeping throughout the supply chain.

Tripoli and Schmidhuber (2020) introduced a framework for optimizing animal traceability using digital technologies like IoT, blockchain, AI, and big data analytics to enhance efficiency, accuracy, and security. The framework includes electronic identification (EID) methods and digital ledger technologies (DLTs) to securely store and share data across the supply chain. AI and predictive analytics are used for monitoring animal health, detecting diseases, and ensuring compliance with food safety standards. The framework also emphasizes the need for supportive policies, infrastructure, and capacity building to facilitate the adoption of these technologies. Together, these components aim to improve animal health management, ensure food safety, simplify trade, and raise consumer awareness.

Arvana et al. (2023) proposed a blockchain-based framework for animal traceability in the agri-food sector, focusing on the production of Portuguese hams. The framework utilizes a multi-layer architecture that includes a business layer to define the supply chain processes, an integration layer for data collection and sharing, a cloud computing layer incorporating blockchain technology for decentralized and immutable data storage, and an application layer for user interaction. Smart contracts are employed to automate the recording and validation of transactions, ensuring data reliability and transparency throughout the entire product lifecycle. The system enhances traceability by capturing detailed information at each stage, from the animal's origin to the final consumer, making the process more transparent and trustworthy. This approach addresses the limitations of traditional centralized traceability systems, reducing the risk of data tampering and increasing consumer confidence in the quality and safety of meat products.

A framework for integrating digital twins (DT) of livestock production into a unified digital platform for agricultural management is proposed by Medennikov (2024). This framework emphasizes using digital twins to model and monitor various aspects of livestock farming, such as feeding, milking, and breeding, ensuring precise traceability and management. The DT framework includes cloud-based sub-platforms for collecting and storing primary data, technological databases for managing farming operations, and a knowledge base for algorithmic management and decision-making. By integrating these components, the framework aims to create a holistic system that connects livestock production with other agricultural sectors like crop production and processing. The unified approach seeks to improve sustainability, enhance breeding practices, and meet global standards for food safety and environmental protection

A framework for integrating blockchain technology into animal healthcare by Walunj and Gourkar (2024) utilizes a permissioned blockchain platform, specifically Hyperledger Fabric, to manage various aspects of animal health data securely and transparently. The proposed framework involves a system design that includes multiple nodes representing authorized entities, such as veterinary clinics, adoption centers, and emergency services, with each node authenticated through a Membership Service Provider (MSP). Smart contracts are utilized within this framework to enforce business rules and access control policies, ensuring that only authorized personnel can update or view specific types of data. This approach aims to enhance privacy, trust, and the traceability of animal health records, contributing to better management of animal healthcare.

Witt et al. (2024) proposed a framework to validate the use of slaughterhouse indicators as proxies for on-farm animal welfare and health assessments in pigs. It integrates data collected from 12 on-farm and seven slaughterhouse indicators, combining them into three health indices: limb health, other organ health, and respiratory health. The study examines the agreement between these indices across different production stages, such as farrowing, rearing, and fattening, to determine the feasibility of using slaughterhouse findings as retrospective indicators of on-farm conditions. The research shows that while some slaughterhouse indicators can partially substitute on-farm assessments, complete replacement is not feasible, and agreement varies with the timing of assessments. Although this framework does not currently incorporate ontologies, an ontology-driven approach, as proposed in our current study, could significantly enhance data integration, consistency, and semantic interoperability, leading to more robust and scalable animal welfare monitoring systems.

## Gaps identified in existing studies

The existing studies reveal several gaps in the application of advanced technologies in the area of animal traceability. The first identified gap is the insufficient focus on integration challenges. While there is acknowledgment of the potential benefits of integrating IoT with mobile apps and networks (Resti et al., 2024), there is limited practical guidance or frameworks on how to effectively implement these integrations, especially in regions with poor Internet connectivity and infrastructure. The second gap is the lack of research on the economic feasibility of the proposed advanced technologies. Many of the technologies discussed, such as IoT, RFID, and blockchain, may face barriers to adoption due to their cost and the lack of incentives for farmers in developing countries to implement these systems. More research is needed to explore cost-effective solutions and economic models that can encourage the widespread adoption of traceability technologies. The last and most important gap is the lack of discussion on data standardization and interoperability. Despite the advances in traceability technologies, there is a noticeable absence of discussion on standardization and interoperability of data across different traceability tools and platforms, which is crucial for achieving seamless integration and effective traceability across various stages of the supply chain.

In addition to the identified gaps in the publications on the use of advanced technologies in animal traceability, there are gaps identified in existing animal traceability frameworks. The first gap is scalability and cost-effectiveness. While several frameworks, such as those using IoT (Addo-Tenkorang et al., 2019) and blockchain technology (Marinello et al., 2017; Arvana et al., 2023), promise enhanced traceability and transparency, they often face challenges in scalability and cost-effectiveness, particularly for smallholder farmers in developing regions. There is a lack of practical solutions that balance high-tech capabilities with affordability and ease of use for broader adoption. The second gap is integration and interoperability. Existing frameworks, like the DBE proposed by Füzesi et al. (2010) and the centralized database systems by Bai et al. (2017), emphasize the importance of data sharing and interoperability. However, there is a need for more comprehensive strategies to integrate various technologies (e.g., RFID, blockchain, mobile apps) into a unified system that ensures seamless interoperability across different platforms and stakeholders, including farmers, regulators, and consumers. The third gap is data privacy and security. Blockchain-based frameworks (Marinello et al., 2017; Arvana et al., 2023) address data security and transparency. However, there is limited discussion on managing data privacy concerns, especially when handling sensitive information related to animal health and owner details. There is a gap in frameworks that offer robust security measures while also maintaining privacy and confidentiality of data. The fourth gap is regulatory and policy support. Several frameworks mention regulatory compliance as a benefit of traceability systems (Chen et al., 2019; Tripoli & Schmidhuber, 2020). However, there is a gap in frameworks providing detailed guidance on aligning these systems with varying international and local regulations. More comprehensive frameworks are needed that include specific policy recommendations and implementation strategies to ensure compliance across different regions.

### The study rationale

The gaps identified in existing studies highlighted opportunities for future research and development to create more inclusive, secure, scalable, and interoperable animal traceability frameworks that consider the economic, social, and technological challenges faced by stakeholders in various settings.

This research aimed to address the existing gap in interoperable, knowledge-based frameworks for developing animal traceability systems and related platforms in Botswana. The lack of interoperability has undermined the effectiveness of promising initiatives like LITS and BAITS. While these systems have succeeded in gathering animal traceability data, they did not offer a standardized and interoperable framework that fully integrated all relevant stakeholders. Currently, these systems mainly serve only two categories of stakeholders (government and farmers), despite the involvement of at least five different categories of stakeholders, as demonstrated by our research, in the animal traceability process. There is a pressing need for a truly interoperable system that brings all stakeholders together within a unified environment, allowing them to access critical information more efficiently, without the constant need for veterinarian intervention for every cattle-related matter. Such a system should support reliable cattle identification through advanced tracking technologies that automatically feed data into the platform. It should also provide user-friendly interfaces in both Setswana and English, reducing reliance on technical terminology. Moreover, a centralized database would enhance the generation and updating of reports, significantly reducing processing times. By promoting data sharing and reuse, this interoperable system would increase the value of collected data, leading to more efficient and effective animal traceability.

This study proposes an ontology-driven framework for animal traceability (ODF-AT) in Botswana, which can be extended to other developing countries. The framework focuses on enhancing interoperability and integration among stakeholders in the livestock sector through ontology-based knowledge management. It is structured into four layers: an input layer for data collection, a semantic core layer for query processing, a knowledge management layer serving as a data hub, and an application layer for user interaction. This framework addresses gaps in scalability, data privacy, and standardization, aiming to improve disease control, food safety, and economic outcomes by providing a comprehensive animal traceability system.

Objectives of this research were stated as follows:

RO1: To identify and analyze the limitations and challenges of current animal traceability frameworks and systems in Botswana.

RO2. To design and develop an ontology-driven framework for animal traceability (ODF-AT) that enhances interoperability, integration, and knowledge sharing among stakeholders in Botswana's livestock sector.

RO3. To evaluate the feasibility and effectiveness of the proposed ontology-driven framework in addressing challenges related to disease control, food safety, and economic outcomes in Botswana.

RO4. To create a scalable and adaptable framework that can serve as a model for implementing animal traceability systems in other regions or developing countries.

The following research questions were derived from the stated research objectives:

RQ1. What are the specific limitations and challenges of current animal traceability systems in Botswana, such as BAITS and LITS, that hinder their effectiveness?

RQ2. What are the key components of an interoperable and knowledge-driven framework for animal traceability in Botswana?

RQ3. How can an ontology-driven approach address the challenges of interoperability and integration in animal traceability systems?

RQ4. What is the impact of the proposed ontology-driven framework on stakeholders' collaboration, data sharing, and overall efficiency in the livestock sector?

RQ5. How can the framework be adapted and scaled for application in other regions with similar challenges in animal traceability?

All the stated research objectives were successfully achieved, and the research questions comprehensively answered in this study.

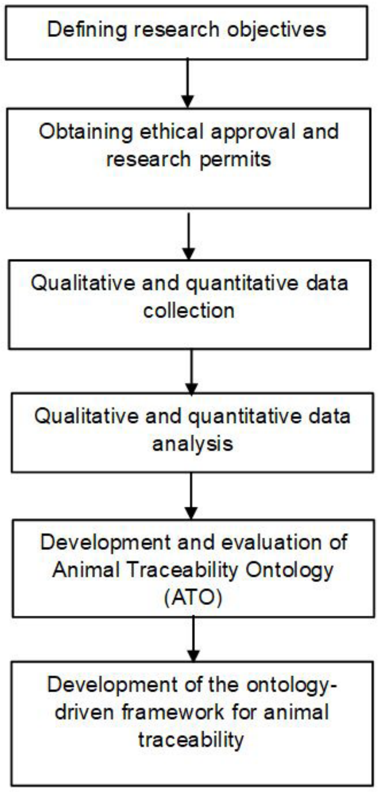
The rest of the paper is organized as follows. Section 2 details the methodology used for developing the ontology-driven framework for animal traceability (ODF-AT). Section 3 presents the results and discusses the findings. Finally, Section 4 concludes the paper and suggests future research directions.

## Materials and methods

This study employed both qualitative and quantitative methods to explore and describe user experiences and the current functionality of animal traceability systems in Botswana (Cresswell & Plano Clark, 2018; Cresswell & Cresswell, 2022). An explanatory research design was adopted, allowing for a comprehensive examination of the challenges and opportunities within animal traceability.

An ethical clearance certificate (HREC-011) was obtained from the research ethics committee at Botswana International University of Science and Technology (Botswana). Additionally, research permits were secured from the Ministry of Agriculture (DVS 7/4/1 VII (90)) and the Ministry of Communications, Knowledge, and Technology (MCKT/1/11/1 I (38)) to authorize interactions with stakeholders.

Data was collected using face-to-face interviews and structured questionnaires, targeting five key categories of stakeholders, including farmers, veterinary professionals, local administrative authorities, officials from the Ministry of Agricultural Development and Food Safety, and representatives from the Botswana Meat Commission. The research involved interviewing various stakeholders to gather comprehensive insights into animal traceability practices. Farm owners and managers were interviewed to provide practical insights into the current animal traceability practices used in the field. Veterinary representatives were consulted to detail the specific tasks they perform related to animal traceability, including health monitoring and documentation. Representatives from the local administrative authorities were engaged to explain the Matimela program (i.e., the management of stray cattle in Setswana), a government initiative aimed at managing stray animals, and its role in traceability efforts. The Ministry of Agricultural Development and Food Safety was involved in providing in-depth information on the BAITS, highlighting its implementation and functionality. Finally, representatives from the Botswana Meat Commission discussed the cattle market dynamics and related systems, offering a broader perspective on the traceability framework within the livestock industry. The purposive stratified sampling method ensured representation across the nine districts of Botswana, with a final sample size of 66 participants. The research process is outlined in Figure 1.




Source: Own elaboration

Figure 1: Steps followed in this research.

In *the data collection stage*, mixed methods were employed to gather qualitative and quantitative data from stakeholders. Data collection tools included semi-structured interviews and questionnaires, targeting a diverse group of participants across the nine districts of Botswana. The collected information was related to current practices, challenges, requirements, and user experiences related to animal traceability.

In *the data analysis stage*, qualitative data was analyzed using content and thematic analysis techniques, facilitated by NVivo 12 software, to identify key themes and patterns. Quantitative data was analyzed using descriptive statistical methods in Microsoft Excel to quantify stakeholder perspectives and challenges.

The next stage involved *the development of the animal traceability ontology* which was at the core of the proposed ontology-driven framework. An ontology defines a common vocabulary for researchers who need to share information in a domain, providing machine-interpretable definitions of basic concepts and the relationships between them (Atanasova, 2011). The ontology was developed using METHONTOLOGY (Fernández-López et al.,

1997) and the Protégé ontology development environment. This involved defining concepts, relationships, data properties, and object properties relevant to animal traceability. The ontology design focused on semantic consistency, scalability, and reusability, allowing for the integration of various data sources and supporting multi-language functionality.

*The development of the ontology-driven framework for animal traceability* was guided by the critical thinking approach. Critical thinking was a core component of the research design, guiding the linkage and analysis of the OD-FAT components (Heard et al., 2020; Paul & Elder, 2020). A critical thinking approach involves systematically evaluating information, identifying patterns, and making informed decisions based on evidence and logical reasoning. By applying critical thinking, one can analyze complex data sets, draw connections, and develop coherent frameworks that address specific problems effectively. In the context of developing an ontology-driven framework for animal traceability, critical thinking was essential for dissecting the relationships between various elements of the system, ensuring that the framework is both comprehensive and practical. This process involved incorporating both the collected data and external data sources to ensure a comprehensive and well-rounded analysis.

In this study, project maps generated by NVivo were utilized to identify patterns and relationships within the collected data, which were crucial for developing the ontology-driven framework (Wilson & Bruni-Bossio, 2020). This method provided a structured visual representation of data, depicting parent and child relationships among key concepts, such as *Farming, Cattle Market, Records*, and *BAITS system*. By illustrating these concepts and their interconnections, the project maps facilitated the identification of possible structures that could inform the ontology-driven framework. The analysis involved linking main concepts to the codes generated per district, enabling a comprehensive understanding of the data and informing the decision-making process for the overall functionality of the proposed framework.

## Results and discussion

### Results and discussion of the quantitative data collection and analysis

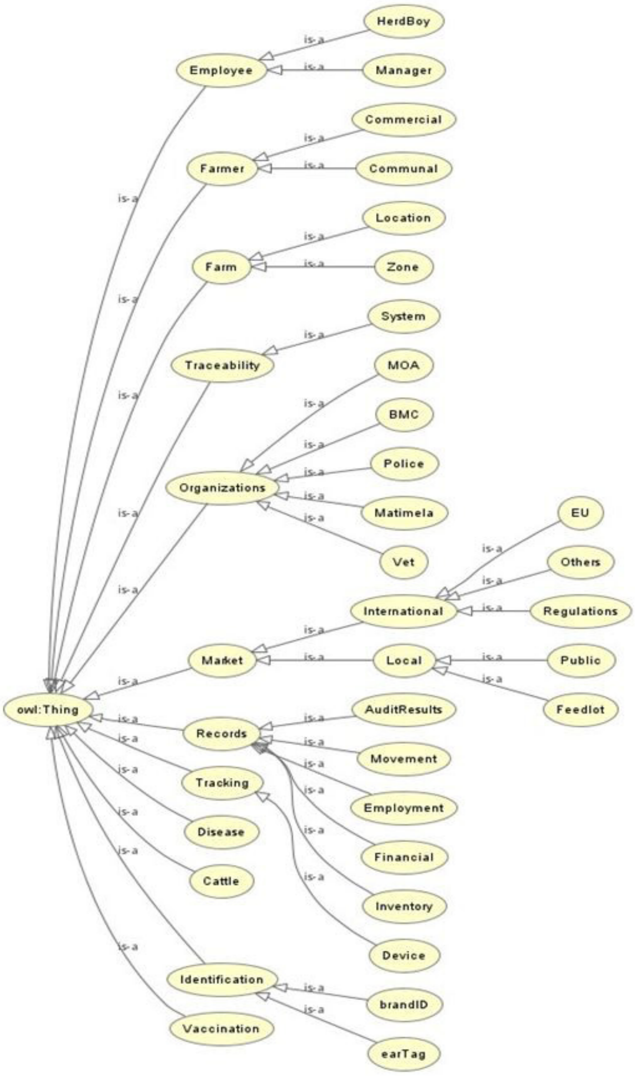
The findings from the collected and analyzed quantitative data centered on respondents' perceptions of the challenges related to animal traceability in Botswana. Participants were asked to rate their perceptions on various aspects of animal identification, tracking, and traceability methods. More than half of participants (55%) indicated that the current methods used by farmers are inadequate, despite 42% making efforts to address these issues. Farmers' associations, established to support various agricultural activities including traceability, were criticized for their ineffectiveness; 56% of respondents expressed that these associations were more about talk than action.

The Matimela program, a government initiative designed to manage stray cattle and prevent theft by housing unclaimed animals in kraals, was also viewed negatively. A significant 85% of respondents believed that the program was ineffective, mainly due to the policy of auctioning unclaimed cattle after 15 days without offering compensation to rightful owners. This has led to dissatisfaction among farmers who often found their cattle sold off without proper notification.

Regarding the BAITS, only 17% of respondents found it useful for identifying cattle, especially in cases where ear tags were still intact. However, 39% felt that BAITS was largely ineffective because enforcement officers and Matimela program administrators rarely utilized it to trace cattle ownership. Consequently, 67% of respondents believed that law enforcement was not doing enough to combat cattle theft. Furthermore, 44% of respondents expressed uncertainty about the usefulness of BAITS, viewing it primarily as a tool for purchasing ear tags and transferring cattle ownership rather than a comprehensive traceability solution.

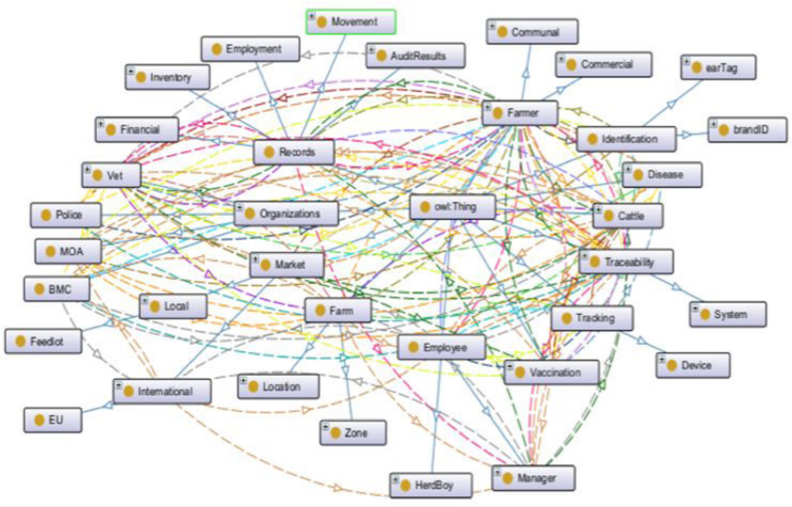
### Results and discussion of the animal traceability ontology development

The animal traceability ontology (ATO) was developed as part of the ontology-driven framework for animal traceability in Botswana to address the challenges of non-interoperable animal traceability systems in Botswana by enhancing communication and data exchange among stakeholders. Stakeholders such as farmers, veterinarians, and regulatory bodies contributed insights that helped refine the ontology to meet real-world needs and practices. The ontology was structured to facilitate knowledge sharing and reusability, supporting efficient tracking and monitoring of cattle. Visualization tools, such as Protégé OWLViz and OntoGraf were used to map out the relationships among different entities, making the ontology easier to understand and implement (Figures 2 and 3).




Source: Own elaboration

Figure 2: Visualization of the ATO with Protégé OWLViz.




Source: Own elaboration

Figure 3: Visualization of the ATO with Protégé OntoGraf.

The ATO was found to be logically sound and free from inconsistencies, ensuring its reliability for practical applications. The evaluation showed that the ATO had a robust structure with rich relationships, making it suitable for detailed traceability tasks. When compared with a reference ontology, Animal Health Ontology (Data-Driven Surveilance, 2024), the ATO demonstrated higher specificity and alignment with the needs of animal traceability, proving its effectiveness in real-world scenarios. Overall, the ATO enhanced the ability to manage, monitor, and track livestock efficiently, supporting knowledge-driven economic opportunities.

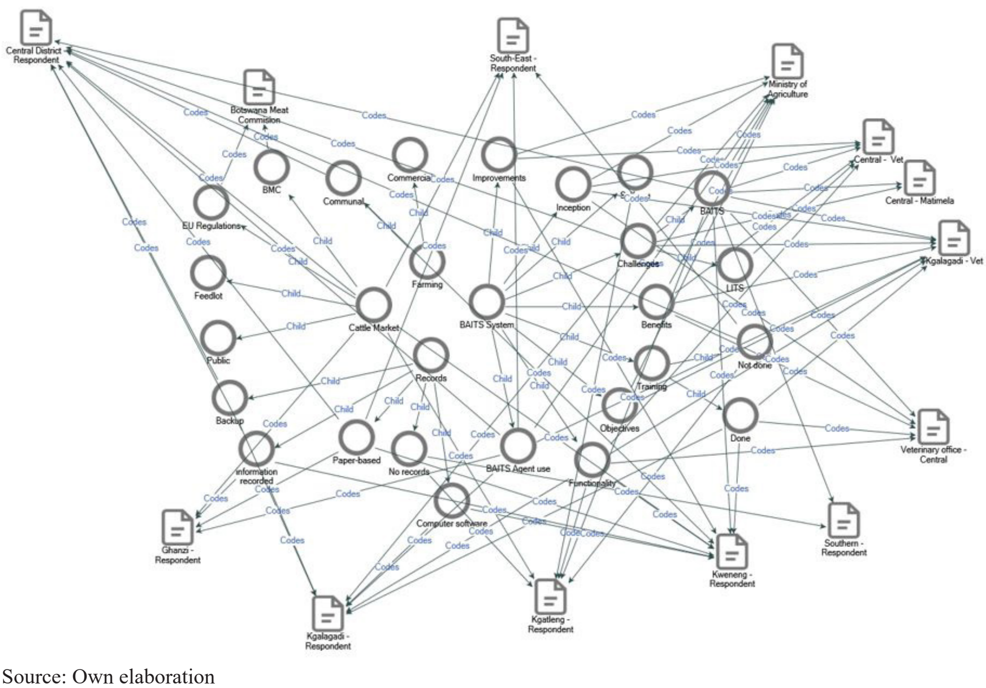
The ATO is not the primary focus of our current paper; it was considered only as one component of the proposed ontology-driven framework for animal traceability in Botswana. The complete ATO is available in Figshare (https://figshare.com/articles/dataset/AnimalTraceability_rdfAnimal_Traceability_Ontology/24461224?file=42977926).

### Results and discussion of the development of the ontology-driven framework for animal traceability (ODF-AT) in Botswana

NVivo project maps were employed in this study to uncover patterns and relationships within the data, which informed the development of the ontology-driven framework. These visual maps were instrumental in outlining the overall functionality and decision-making processes of the framework, as they provided a clearer picture of how different concepts are interconnected. As highlighted by Wilson and Bruni-Bossio (2020), visual project mapping effectively represents logical and cognitive processes, making it a valuable tool in structuring this study's framework. One example of the project map in Figure 4 depicts parent-child relationships essential for understanding the complex interactions within the animal traceability domain. By visualizing the main concepts, such as Farming, Cattle Market, Records, and BAITS system, alongside their associated child relationships, the project map facilitated a comprehensive view of the data. This visualization also linked the main concepts to specific codes generated from district-level data, providing deeper insights into regional variations in traceability practices.

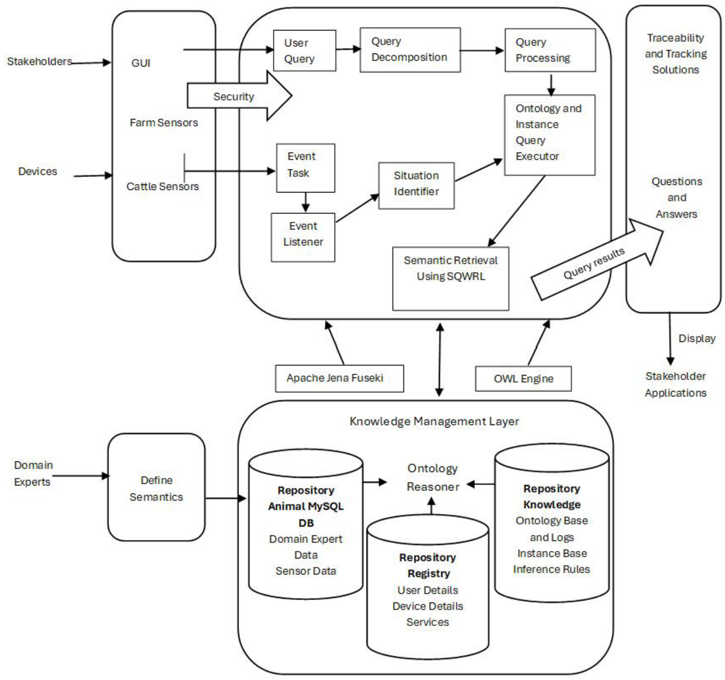
These visualizations contributed to the development of the ontology-driven framework by organizing data relationships, which will ultimately enhance data sharing and interoperability.

Figure 5, presenting the ontology-driven framework for animal traceability, illustrates the guiding principles for building systems, websites, applications, and databases related to animal traceability.




Source: Own elaboration

Figure 4: A project map illustrating the four main concepts within the animal traceability domain (*Farming, Cattle Market, Records,* and *BAITS system*) and their coding relationships across different districts.




Source: Own elaboration

Figure 5: The ontology-driven framework for animal traceability in Botswana.

This framework offers a standardized, integrated, semantic approach to managing traceability data, addressing the evolving challenges in the field. Comprising four layers − input, semantic core, knowledge management, and application − the framework facilitates seamless data flow and knowledge management.

## The input layer of the ODF-AT

The input layer is supplied by several sources. The first source consists of stakeholders who directly input data or submit queries via the graphical user interface. These stakeholders include farmers, veterinarians, the Ministry of Agricultural Development and Food Safety, the Botswana Meat Commission, Matimela officers, and police officers. Another source of input is sensor devices placed on cattle and farms, which monitor conditions and trigger alerts. Information and alerts generated by these devices feed into the input layer, providing real-time data. The final source of input comes from domain experts specializing in animal traceability, who contribute valuable insights that are directed to the knowledge management system.

Farm location and the surrounding environment significantly influence the development of the system. These factors determine the type of sensor devices suitable for use in specific areas. Farmers often face challenges in using certain systems due to the remote locations of their farms, which may lack Internet connectivity. Developers should consider designing systems that can function with satellite technology to accommodate these remote areas. The type of farm − commercial or communal − also affects sensor device choices and system priorities. Commercial farms focused on business objectives, have different requirements compared to communal farms that rear cattle for family sustenance. Communal farmers often need tracking sensors more urgently because their cattle graze freely and are more vulnerable to theft. In contrast, commercial cattle typically graze within enclosed areas, allowing for easier monitoring and management. Commercial farmers can use sensors for counting livestock, monitoring health and behavior, tracking heat periods, and managing disease control. While these sensors are equally beneficial to communal farmers, they especially require tracking devices to prevent theft. Currently, Botswana's animal traceability system does not incorporate sensor devices to capture critical cattle-related data.

## The semantic core layer of the ODF-AT

Within the semantic core layer, the process begins with a security authentication check for users logging into the system. This check ensures the protection of stakeholders' private information and determines user identity and access privileges.

Each user has specific viewing and editing rights within the system. If a user is authorized, their query advances to the next layer for processing; otherwise, an error message is returned. In this layer, user queries and device-generated alerts are handled. Each user query is first registered in the system, and query processing begins by breaking down the query from a high-level format into a relational algebra query. The query undergoes checks for semantic and syntactic correctness, involving semantic analysis, simplification, and restructuring.

The decomposed query is then processed by the query processor, which forwards it to the ontology query executor for verification. The ontology query executor follows a four-step process. It first checks the cache for an existing execution plan. If no plan exists, the query parser sends it through the semantic retrieval tree, using SQWRL to access the knowledge management layer. SQWRL acts as the query language, defining SQL-like operations for the ontology query executor. It constructs specifications for retrieving information stored in the ontology base. This method of semantic retrieval leverages ontological properties, concepts, instances, SQL statements, and production rules. Through this setup, the animal traceability system effectively aligns user query intentions with the knowledge base, ensuring accurate and relevant information retrieval.

### The knowledge management layer of the ODF-AT

The knowledge management layer includes the MySQL database repository, the ontology reasoner, and the ontology base with associated logs. This layer is designed to describe complex situations and their related animal traceability concepts. The first repository stores data from sensor devices and input from domain experts, capturing all raw information. MySQL is used to transform this raw data into more structured and organized information for better management and analysis. The second repository houses the ontology base and logs, where ontologies are stored as OWL files, managed by administrators, and used to deduce relevant knowledge. This repository also contains instances representing various concepts such as OWL files, electronic documents, and HTML pages, which are crucial for developing new ontology constructs and making decisions about modifying existing constructs.

Ontology logs within the repository track actions and operations performed on the ontologies, serving as a tool for recovering from data or system corruption and inconsistencies. Recovery processes involve reviewing uncommitted queries in the logs and rolling back changes as necessary. The third repository includes registries for user details, device details, and services. The user details registry provides semantic descriptions of users' profiles and preferences, while the device details registry offers information about sensor device status and configurations. The service registry supplies functional services based on the location and context of service deployment, linking events with appropriate action services.

The ontology reasoner, also known as the semantic rules engine, infers logical consequences from axioms defined in OWL. It handles query answering by evaluating knowledge representations in the ontology against inputs from animal traceability repositories. Initially, the reasoner checks if the ontology structure meets the specified axioms; if not, it issues a warning message. If the structure is valid, the reasoner proceeds to retrieve query results based on inference rules. The reasoner converts user requests into SQWRL query statements and returns results to the user. This process ensures that the animal traceability model remains logically consistent and reliable.

Apache Jena Fuseki is a SPARQL server that can function as a standalone server or an operating system service. SPARQL, a standard for querying and updating, allows users and developers to focus on the information they seek rather than database organization. Apache Jena Fuseki supports semantic web applications by facilitating efficient information retrieval and management. The OWL Engine works alongside the ontology reasoner to handle animal traceability queries, establishing protocols for communication between users and the system, and managing responses based on knowledge representation.

### The application layer of the ODF-AT

The results of the query processed within the knowledge management layer are then forwarded to the application layer. The application layer computes these results and presents them to stakeholders through the graphical user interface (GUI), functioning as the final output phase. This layer showcases the developed systems and applications, which are delivered to users, allowing them to interact with the system through the GUI. As illustrated in Figure 5, this outcome phase is directly connected to stakeholders, who serve as the end users of the system.

A critical consideration is the language used by the system for communication. In Botswana, existing systems face language barriers as most users are more comfortable with the native language, Setswana, whereas the systems typically communicate in English. To address this issue, developers should implement bilingual support, offering communication in both Setswana and English to accommodate all users. Once the system has been tested and finalized, it should be deployed with comprehensive documentation and user manuals. Conducting training sessions for users is essential, as the lack of adequate training has been a shortcoming in current systems in Botswana. These training courses will help users understand and utilize the system effectively. Moreover, training sessions provide an opportunity for developers to identify any issues and make necessary adjustments early on. Ongoing maintenance is crucial to ensure the system remains functional and up to date, with regular updates and fixes implemented as part of this ongoing support process.

## Conclusion

### Key findings and their alignment with research objectives and questions

This study introduced an ontology-driven framework for animal traceability (ODF-AT) in Botswana to address key challenges of interoperability, integration, and standardization in existing systems. By incorporating advanced technologies such as ontology-based knowledge management, sensor devices, and secure data processing, the framework ensures efficient and reliable livestock traceability from farm to fork. It effectively addresses gaps in scalability, data privacy, and standardization, offering potential improvements in disease control, food safety, and economic outcomes for Botswana's livestock sector.

The research objectives were successfully met, beginning with the identification and analysis of limitations in current animal traceability systems, such as BAITS and LITS. Using a combination of literature review, semi-structured interviews, and structured questionnaires with stakeholders—including farmers, veterinarians, government officials, and Botswana Meat Commission representatives—the study identified challenges such as poor interoperability, limited stakeholder engagement, and inadequate use of tracking technologies.

The second objective, the design of the ODF-AT, was achieved using the METHONTOLOGY methodology and the Protégé development environment. Insights from stakeholders and literature informed the creation of a four-layer framework—input, semantic core, knowledge management, and application—ensuring seamless integration and data interoperability. The framework integrates advanced features, including real-time data processing and user-friendly interfaces.

The third objective evaluated the framework's feasibility and effectiveness. Logical consistency checks and comparative analysis validated the Animal Traceability Ontology (ATO), a core component of the framework, ensuring alignment with practical needs. Stakeholders confirmed that the framework enhances communication and data sharing, addressing critical traceability challenges.

The final objective focused on scalability and adaptability. The framework's modular design supports integration with various technologies and contexts, enabling application in other regions and for additional livestock or agricultural products. Future research directions suggest tailoring the framework to local needs, including multi-language support and cost-effective technologies.

The study also answered key research questions. It identified limitations in current systems, such as lack of interoperability, inadequate technology use, and insufficient enforcement mechanisms. It outlined essential framework components, demonstrated how ontology-driven approaches address integration challenges, and highlighted the framework's positive impact on collaboration, data sharing, and operational efficiency. Lastly, it detailed the framework's adaptability for other regions with similar traceability challenges.

Overall, this study achieved its objectives and provided a comprehensive solution to enhance animal traceability in Botswana and beyond.

### Implications for theory, policy, and practice

Theoretically, this research highlights the value of ontology-driven frameworks in addressing challenges related to interoperability, integration, and data standardization in complex systems. The proposed framework demonstrates how advanced knowledge management techniques can enhance traceability processes, providing a structured approach that aligns with evolving technological and methodological advancements.

From a policy perspective, the study emphasizes the importance of regulatory frameworks that support the adoption of interoperable and scalable systems. It underlines the need for policies that address data privacy, stakeholder collaboration, and infrastructure development, ensuring alignment with international trade requirements and food safety standards. These insights can guide policymakers in creating supportive environments for implementing traceability systems.

Practically, the study provides a scalable and adaptable framework for improving animal traceability in Botswana and similar contexts. It incorporates advanced technologies such as sensor devices and knowledge management tools to enhance real-time data collection and processing. The framework's emphasis on user-friendly interfaces and multilingual support ensures accessibility for diverse stakeholders. By addressing gaps in current systems, the research contributes to improving disease control, food safety, and economic outcomes, offering a practical solution for stakeholders across the livestock sector.

### Study limitations and future research

Despite the promising results, this study has several limitations that highlight opportunities for future research. First, the ODF-AT framework is tailored to the Botswana context, and its applicability in other developing regions with distinct socio-economic and environmental conditions may require significant adjustments. Future research should focus on customizing and adapting the framework for use in diverse settings, conducting comparative studies to assess its adaptability and effectiveness across different contexts.

Second, the deployment of advanced technologies, such as ontology-based knowledge management and sensor devices, faces practical challenges in rural and remote areas of Botswana. Limited Internet connectivity, inadequate infrastructure, and high technological costs could hinder full-scale implementation. Addressing these issues calls for exploring alternative solutions, such as satellite-based communication systems, and developing affordable sensor devices that cater to small-scale farmers. Partnerships with technology providers and government agencies could facilitate these advancements.

Third, the study's focus on cattle reflects its economic and food security significance in Botswana, but the framework's potential for broader agricultural applications remains unexplored. Expanding the framework to include other types of livestock and agricultural products would create a comprehensive traceability solution, supporting food safety and quality across various sectors. Collaborative efforts with experts from different agricultural domains are essential for refining the framework to meet diverse stakeholder needs.

Fourth, while the framework incorporates security and data privacy measures, continuous updates are needed to counter evolving cybersecurity threats. Implementing advanced encryption techniques, multi-factor authentication, and regular security audits would enhance data protection and compliance with privacy regulations. Future work should prioritize collaborations with cybersecurity experts to strengthen the framework's resilience.

Fifth, the success of the ODF-AT depends heavily on stakeholder engagement and cooperation. Resistance to change, lack of awareness, and limited technical expertise may pose barriers to adoption. Comprehensive training programs and awareness campaigns tailored to various stakeholder groups are crucial for addressing these challenges and ensuring active participation. Building a strong network of informed and collaborative stakeholders will enhance the framework's acceptance and functionality.

Lastly, while the study's evaluation of the ODF-AT relied on qualitative and quantitative methods, further empirical testing is required to validate its real-world effectiveness. Pilot projects and case studies should be conducted to assess the framework's impact on animal traceability, disease control, food safety, and economic outcomes. These initiatives would provide valuable insights for iterative improvements, enabling the framework to maximize its potential and scalability. By linking these limitations to targeted research efforts, the study lays a clear foundation for advancing animal traceability systems in Botswana and beyond.

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