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LEVERAGING ONTOLOGY-BASED KNOWLEDGE MANAGEMENT FOR IMPROVED DATA QUALITY AND ENHANCED TRADE COMPLIANCE IN LIVESTOCK TRACEABILITY SYSTEMS IN BOTSWANA

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ABSTRACT

Aim/Purpose	The problem addressed by this research is the struggle of Botswana's livestock sector to implement effective animal traceability systems due to limited interoperability, inadequate data integration, reliance on open grazing systems, and systemic challenges like high mortality, theft, and disease outbreaks. These challenges collectively undermine animal traceability system competitiveness and compliance with international trade standards.
Background	The paper addresses the problem by developing the Animal Traceability Ontology (ATO), standardizing data representation, and enabling seamless data sharing among stakeholders in Botswana's livestock industry. This ontology im-

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	proves interoperability, real-time data integration, and trade compliance, ultimately enhancing disease management and compliance with international trade standards.
Methodology	The paper employed a mixed-methods research design, combining qualitative data collection through interviews and focus groups with stakeholders (such as farmers, veterinarians, and officials) and quantitative data through structured questionnaires. The ontology was developed using METHONTOLOGY, a widely adopted approach for ontology creation, and was evaluated using tools such as Protégé, Apache Jena Fuseki, and the Pellet reasoner. The research sample included key stakeholders in Botswana's livestock industry, including farmers, veterinary officers, and representatives from the Botswana Meat Commission.
Contribution	This research developed the ATO to enhance data quality and interoperability in livestock traceability systems. The ATO's practical implications include fostering stakeholder collaboration, supporting small-scale farmers, enabling real-time disease management, and driving sustainable livestock practices. It addresses data heterogeneity and limited integration, providing a scalable framework for decision-making and compliance with international trade standards and offering a practical model to improve traceability across diverse systems.
Findings	The evaluation of the ATO assessed its structural, usability, and functional aspects, demonstrating its logical adequacy, stakeholder relevance, and performance efficiency. A comparative analysis with the Animal Health Ontology (AHO) revealed the ATO's superior inheritance richness, relationship diversity, and tailored design for precise traceability applications, ensuring enhanced data integration, semantic clarity, and practical functionality for animal traceability systems. The ATO was, therefore, found to be a robust solution to Botswana's livestock traceability challenges. The ATO has the potential to enhance Botswana's livestock traceability by improving data quality, interoperability, real-time processing, and stakeholder collaboration, offering scalable tools for disease management, trade compliance, and sustainable livestock management.
Recommendations for Practitioners	Farmers should adopt affordable, user-friendly tools like mobile apps or compatible devices to streamline data entry and tracking. Regulatory agencies should promote training, ensure compliance with traceability standards, and provide subsidies for small-scale farmers. Collaboration among stakeholders will enhance system usability, real-time updates, and alignment with international trade standards.
Recommendations for Researchers	The paper recommends that researchers leverage METHONTOLOGY for systematic ontology development, use tools like Protégé for evaluation, apply the ATO framework (or similar frameworks) to improve interoperability in other sectors, investigate its role in compliance and disease management, and examine its real-time data integration capabilities.
Impact on Society	The ATO has the potential to positively impact farmers by streamlining livestock management, enabling efficient disease monitoring, reducing mortality rates, and boosting productivity and economic stability. For regulatory agencies, it ensures adherence to international trade standards, facilitates global market access, enhances public health, strengthens food safety, and bolsters national food security. Additionally, the ATO fosters collaboration and seamless data sharing among veterinarians, governmental and parastatal organizations (e.g.,

	the BMC), and law enforcement, enhancing disease management, expanding market opportunities, and mitigating livestock theft.
Future Research	Future research should explore the scalability of ATO (or similar ontologies), integrate advanced technologies like blockchain and IoT, develop simplified versions for resource-limited settings, expand research on real-time data analytics, and collaborate with industry stakeholders for practical alignment.
Keywords	ontology-based knowledge management, data interoperability, livestock traceability systems, trade compliance, systems integration, data quality enhancement

INTRODUCTION

Effective animal traceability systems are essential for managing livestock health, ensuring food safety, and facilitating international trade. At the basic level, such systems require components like animal identification, information flow management, and centralized databases to store and manage data (Bai et al., 2017). The World Organisation for Animal Health has been a key player in establishing international standards for these systems, focusing on the identification of individual animals, tracking their movements, and maintaining accurate records. The Terrestrial Animal Health Code (World Organisation for Animal Health, 2024) includes provisions on traceability, specifically addressing the design and implementation of identification systems to achieve animal traceability and general principles for the identification and traceability of live animals. These are critical for improving disease management, trade compliance, and the coordination of animal health measures. Effective traceability from farm to fork is critical for disease control, food safety, and reducing trade barriers (Vallat, 2009). One example is the Agri-Traceability Québec (ATQ) system, which focuses on centralizing traceability data for different agricultural sectors into multispecies databases (Lavoie & Forest, 2009). Similarly, other systems tend to prioritize tracking devices over comprehensive data management, often relying on post-slaughter data collection methods (Zhao et al., 2020).

The need to control cattle diseases has been a driving force behind the development of animal traceability systems. The public health risks associated with cattle diseases have led to stricter trade regulations, such as the World Trade Organization's (1998) sanitary and phytosanitary measures. Additionally, European Union regulations (articles 112 to 115 of Regulation (EU) 2016/429) have imposed rigorous requirements for the import and export of cattle, necessitating the implementation of effective traceability systems (European Commission, 2024; European Union, 2019). These international standards compel countries and farmers to adopt comprehensive animal traceability measures to manage livestock effectively and comply with global trade requirements.

Existing animal traceability systems face challenges, including limited interoperability, poor data integration, and compliance with regulatory standards. Interoperability is a major concern, as pointed out by Koncová and Kremeňová (2022), because it enables efficient communication, data protection, improved productivity, consistent data management, and cost reduction.

BACKGROUND INFORMATION ON LIVESTOCK PRODUCTION IN BOTSWANA

Agriculture is a vital component of livelihood for many people in Botswana, even though it contributes only around 2% to the country's GDP (Mann, 2024). The sector is primarily dominated by livestock production, especially cattle, which constitutes roughly 80% of the agricultural GDP (Mann, 2024). Botswana's beef heritage is deeply intertwined with its socio-economic and cultural history, highlighting the importance of cattle as both a livelihood and a symbol of identity (Chatibura, 2023). The country's free-range, grass-fed beef is known for its high quality and unique flavor (Botswana Meat Commission, 2024). Botswana cattle production systems employ technologies like electronic rumen boluses for traceability to ensure compliance with stringent international market standards.

The Ministry of Agricultural Development and Food Security, commonly known as the Ministry of Agriculture (MoA), is tasked with enhancing food security and fostering agricultural development in Botswana (Government of Botswana, 2022). The Ministry's efforts span several departments and parastatals, aiming to diversify the agricultural sector, reduce reliance on imports, enhance value addition, and promote sustainable practices. Specifically, the Department of Animal Production (DAP) seeks to enhance the competitiveness of Botswana's livestock sector by reducing reliance on imports, transferring skills and technologies, providing expert advice, and supporting both subsistence and commercial farmers in improving productivity and sustainability. A parastatal organization, Botswana Meat Commission (2024), established in 1965, aims to sustainably produce premium meat for the global market.

Development Challenges Facing Botswana

The sharp decline in Botswana's cattle population from 2010 to 2019 is attributed to poor farm management, low birth rates, high mortality, and theft (Gofamodimo, 2022). Climate change-induced droughts, like the severe 2015/2016 drought, significantly worsened these challenges, impacting both livestock numbers and water resources. Additionally, the number of cattle holdings dropped drastically, with over 62% of farmers leaving the sector, reflecting systemic issues in the sustainability of livestock farming in Botswana. These challenges highlight the critical need for improved management practices, the adoption of climate-resilient strategies, and enhanced traceability systems to stabilize and grow the livestock industry.

The 2023 report by the Food and Agriculture Organization of the United Nations (2023) includes statistical data demonstrating that livestock production in Botswana significantly contributes to hidden costs in agrifood systems, particularly through environmental impacts such as greenhouse gas emissions and land degradation, reflected in the high climate costs. Limited access to markets and technological adoption also exacerbate inefficiencies, as does the lack of secure land tenure in communal grazing areas, discouraging investment in improved livestock management practices (Temoso et al., 2016).

Challenges Facing Botswana's Animal Traceability Systems

Effective animal traceability systems are essential for managing livestock health, ensuring food safety, and facilitating international trade. At the basic level, such systems require components like animal identification, information flow management, and centralized databases to store and manage data (Bai et al., 2017). Botswana employs the Botswana Animal Identification and Traceability System (BAITS), designed to enhance livestock traceability from birth to slaughter. It mandates the use of electronic and analog ear tags, ensuring accurate identification and traceability of cattle while requiring farmers to report movements, departures, and mortalities to a centralized database within specified timelines (Ministry of Agricultural Development and Food Security, 2018).

Despite these measures, Botswana faces numerous challenges in maintaining effective traceability systems. These include limited interoperability, poor data integration, and compliance with regulatory standards. The reliance on open grazing systems complicates accurate tracking of individual cattle and contributes to low productivity and elevated mortality rates in communal grazing areas (Dizyee et al., 2017). Furthermore, foot-and-mouth disease (FMD) outbreaks disrupt cattle movement and trade, undermining the effectiveness of existing traceability frameworks. The annual agricultural survey by Statistics Botswana (2020) revealed that cattle losses from theft and straying remained high, emphasizing gaps in traceability systems.

The Performance of Veterinary Services (PVS) evaluation report by the World Organisation for Animal Health (2011) highlighted critical challenges in animal traceability that remain relevant more than 10 years later, such as inadequate infrastructure and resources, limited veterinary personnel, and high costs of physical barriers for disease management. Addressing these challenges requires investments in modern traceability systems, enhanced disease control, and stakeholder coordination to improve the sector's competitiveness and market access.

THE RESEARCH RATIONALE

Botswana's livestock sector struggles with implementing effective animal traceability systems due to limited interoperability, inadequate data integration, reliance on open grazing systems, and systemic challenges like high mortality, theft, and disease outbreaks, which collectively undermine its competitiveness and compliance with international trade standards. In response to these critical issues, this research developed an Animal Traceability Ontology (ATO) specifically tailored to the needs of Botswana's livestock industry. By addressing the limitations of existing systems, the ATO enhances interoperability, standardizes vocabularies, and improves data integration, offering a robust framework to tackle the challenges posed by open grazing systems and systemic inefficiencies. This ontology-driven approach supports better data sharing among stakeholders, strengthens disease management efforts, and ensures compliance with stringent international trade standards, positioning Botswana's livestock sector for improved competitiveness and sustainable growth.

The rest of the paper is organized as follows: related work on traceability ontologies, the methodology used for developing the ATO, the results and discussion of the findings from each development phase, and the conclusion and future research directions.

RELATED WORK

TECHNICAL BARRIERS AND IMPLEMENTATION CHALLENGES FOR SMALL-SCALE LIVESTOCK PRODUCERS IN DEVELOPING COUNTRIES

Bahta and Malope (2014) identified several technical barriers for small-scale livestock producers in Botswana, including limited market access, high input costs (e.g., feed and veterinary services), and inadequate infrastructure, which collectively hinder profitability and competitiveness. Additionally, challenges such as low education levels, market distance, and resource constraints exacerbate inefficiencies in smallholder systems. Temoso et al. (2016) emphasized the low adoption of advanced breeding and feeding technologies, poor management practices, and limited access to markets and infrastructure as significant technical barriers. Traditional production systems, which dominate small-scale farming, face inefficiencies due to open grazing systems, inadequate land tenure security, and vulnerability to disease outbreaks, such as FMD. These issues are further exacerbated by the semi-arid environment, high livestock mortality rates, and limited capacity for technology transfer, making it difficult for smallholders to compete with commercial systems and achieve sustainable productivity. Dizyee et al. (2017) examined systemic challenges within Botswana's communal grazing systems, identifying key technical barriers such as limited access to disease control measures like FMD vaccinations, inadequate traceability systems, and reliance on low productivity open grazing systems that hinder compliance with export standards. The monopolistic control of the Botswana Meat Commission further restricts market access. It depresses prices for smallholders, underscoring the need for policy reforms and investments in disease control, infrastructure, and market diversification. More recently, Bahta et al. (2023) highlighted additional technical barriers, including limited access to advanced technologies, inadequate data management systems, and a lack of interoperability among existing traceability tools. Implementation challenges are compounded by infrastructure deficits, such as unreliable Internet connectivity and electricity, alongside low technical literacy among producers. These constraints impede the adoption of robust livestock traceability systems, creating significant obstacles to enhancing food security, economic sustainability, and compliance with international trade standards.

Similar technical barriers and implementation challenges exist in other developing countries. The review paper by Mwanga et al. (2020) highlights the technical barriers faced by small-scale livestock producers in African countries, including poor record-keeping systems, reliance on traditional identification methods like branding, limited access to ICT infrastructure, and advanced technologies such as RFID. These challenges are exacerbated by fragmented data, low technical literacy, and inadequate network coverage, making it difficult for farmers to implement efficient traceability systems and meet international standards. To overcome these barriers, the paper emphasizes the need for integrated ICT-driven solutions, improved infrastructure, and capacity-building initiatives to support evidence-based decision-making and enhance livestock traceability from farm to fork. van Marle-Köster et al. (2015) considered technical barriers faced by small-scale livestock producers in countries of Southern Africa, including limited access to advanced genomic technologies due to high costs, inadequate infrastructure, and a lack of skilled personnel to implement these innovations effectively. Smallholders also were facing challenges related to poor extension services, insufficient knowledge transfer, and limited integration of genomic tools into traditional livestock practices. Additionally, fragmented data systems and inconsistent policy support hindered the adoption of genomic technologies, leaving small-scale producers unable to fully benefit from their potential to improve livestock productivity and resilience. Resti et al. (2024) identified several technical barriers and implementation challenges faced by small-scale livestock producers in several developing countries (India, Kenya, Malawi, Thailand, and South Africa). Key obstacles include unreliable Internet connectivity, lack of user-friendly interfaces, high initial costs for technology infrastructure, and the predominant reliance on manual data entry. Additionally, limited farmer training, inadequate stakeholder collaboration, and fragmented systems that fail to integrate core components such as traceability and performance monitoring exacerbate these challenges, hindering the adoption of advanced digital solutions for livestock management.

The study by Ramadhan et al. (2021) identifies technical barriers for small-scale livestock producers in Indonesia, including inadequate access to advanced technologies for animal health monitoring, limited infrastructure for efficient animal traceability, and challenges in adopting modern dairy recording tools due to low digital literacy and internet connectivity issues. Implementation challenges are compounded by fragmented stakeholder coordination, insufficient government support for subsidizing technology adoption, and a lack of training programs to enhance farmers' technical skills. The study highlights the need for tailored solutions such as mobile-based tools, affordable technology options, and multi-stakeholder collaboration to overcome these barriers and improve the productivity and sustainability of small-scale livestock farming in Indonesia. Alarcon et al. (2017) named and discussed several technical barriers and implementation challenges for small-scale livestock producers in Kenya, particularly in Nairobi's beef, sheep, and goat food systems. Key issues include the lack of infrastructure for cold storage, quality control, and transport, which limits market access and profitability for smallholders. Additionally, the absence of traceability systems and poor disease management frameworks increase health risks and reduce the competitiveness of small-scale producers, while their dependence on informal and inefficient value chains intensifies these challenges. The paper by Prinsloo and de Villiers (2017) emphasized the technical barriers encountered in Namibia during the implementation of the Namibian Livestock Identification and Traceability System (NamLITS). Challenges included the lack of infrastructure in the Northern Communal Areas (NCAs), inadequate training of animal technicians, and difficulties in integrating communal farmers into a system designed for commercial operations. The NCA refers to a region in Namibia located north of the Veterinary Cordon Fence. It is primarily inhabited by communal farmers, who rely on subsistence farming and livestock for their livelihoods. Unlike the southern commercial farming regions, the NCAs have historically faced restrictions on exporting their meat products due to their proximity to wildlife that poses a higher risk of transmitting diseases like FMD. Additionally, the need for consistent monitoring, disease control measures, and unique animal identification methods posed significant implementation hurdles, underscoring the importance of localized solutions and stakeholder engagement. Another study from Namibia also focusing on implementation of NamLITS outlined the technical barriers specifically for sedentist small-scale livestock farmers who rely on fixed locations for farming (Mauerman et al., 2023). These barriers include the limited availability of advanced technologies, such as RFID systems for traceability, which are expensive and require skilled personnel to operate. Challenges also stem from poor infrastructure in rural areas, including inadequate veterinary services and limited access to digital tools for livestock management, which are especially critical for sedentist farmers due to their reliance on localized resources.

Furthermore, there is a gap in training and capacity building, leaving many small-scale farmers, including sedentists, unable to fully adopt or benefit from modern livestock traceability systems. In Thailand, significant technical barriers faced by small-scale livestock producers, including limited access to technology for livestock traceability and the lack of infrastructure to support its implementation (Kampan et al., 2022). Challenges such as high costs, insufficient technical knowledge, and inadequate training among farmers hinder the adoption of advanced technologies like blockchain, making it difficult for small-scale producers to meet international market requirements. Furthermore, a lack of coordinated policies and support from government and industry stakeholders exacerbates the difficulty of overcoming these barriers, leaving small-scale producers at a disadvantage in terms of productivity and market access.

Table 1 presents a summary of the reviewed studies on technical barriers and implementation challenges for small-scale livestock producers in developing countries.

Table 1. A summary of the reviewed studies on technical barriers and implementation challenges for small-scale livestock producers in developing countries

S/N	Reference	Countries	Technical barriers	Implementation challenges
1	Bahta and Malope (2014)	Botswana	Limited market access, high input costs, inadequate infrastructure	Low education levels, market distance, resource constraints
2	Temoso et al. (2016)	Botswana	Low adoption of advanced technologies, poor management, disease vulnerability	Semi-arid environment, high livestock mortality, inadequate technology transfer
3	Dizyee et al. (2017)	Botswana	Limited disease control, inadequate traceability, reliance on low productivity	Monopolistic Botswana Meat Commission control, policy gaps, infrastructure deficits
4	Bahta et al. (2023)	Botswana	Limited access to advanced technologies, inadequate data management	Infrastructure deficits, low technical literacy, lack of interoperability
5	Mwanga et al. (2020)	African countries	Poor record-keeping, reliance on branding (i.e., using physical marks, such as hot iron or freeze branding, to identify livestock), limited ICT access	Fragmented data, low technical literacy, inadequate network coverage

S/N	Reference	Countries	Technical barriers	Implementation challenges
6	van Marle-Köster et al. (2015)	Countries of Southern Africa	Limited access to genomic technologies, poor extension services	High costs, lack of skilled personnel, fragmented data systems
7	Resti et al. (2024)	India, Kenya, Malawi, Thailand, South Africa	Unreliable Internet, manual data entry, high tech costs	Limited farmer training, fragmented systems, inadequate stakeholder collaboration
8	Ramadhan et al. (2021)	Indonesia	Inadequate animal health monitoring, limited traceability infrastructure	Fragmented coordination, insufficient government support, lack of training programs
9	Alarcon et al. (2017)	Kenya	Lack of cold storage, poor quality control, absent traceability systems	Informal value chains, poor disease management, inadequate transport infrastructure
10	Prinsloo and de Villiers (2017)	Namibia	Inadequate NCA infrastructure, lack of training	Difficulty integrating communal farmers, need for localized solutions
11	Mauerman et al. (2023)	Namibia	Expensive RFID systems, limited veterinary services	Poor rural infrastructure, training gaps
12	Kampan et al. (2022)	Thailand	Limited access to blockchain, lack of traceability	High costs, insufficient technical knowledge, lack of government support

It should be noted that none of the reviewed studies used or proposed using ontologies as a solution for identified barriers and challenges. Moreover, the traceability ontologies in food supply chains are only found outside Sub-Sharan Africa, mostly in developed countries, as demonstrated in the next subsection.

An Overview of the Traceability Ontologies in Food Supply Chains

Animal traceability ontologies are essential tools for managing and monitoring livestock data, offering a structured approach to defining and categorizing various aspects of animal identification and tracking. This study identified and critically reviewed several relevant food supply chain traceability ontologies, although only a few were specifically concerned with animal traceability.

The paper by Magliulo et al. (2013) explores the application of ontologies in the dairy supply chain to improve traceability, using the Bovlac project, an initiative focused on enhancing traceability within the dairy supply chain, particularly in the production of traditional cheese, as an example. Ontologies are used to model business processes and define rules, enabling consistent representation and sharing of data related to product quality and production methods across different supply chain stages. By formalizing the relationships between various elements such as milk characteristics, production processes, and product origins, ontologies ensure accurate, transparent, and real-time traceability information that can be accessed by consumers. The ValueGo platform, developed for this project, integrates these ontologies with ICT tools like radio frequency identification (RFID), near-field communication (NFC), and quick-response (QR) codes, allowing consumers to retrieve detailed product information by scanning codes with smartphones. This approach demonstrates the effectiveness of ontologies in enhancing data integration, interoperability, and consumer trust, providing a reference for developing similar ontology-driven traceability systems in other domains, including animal traceability.

The TraceFood framework incorporates sector-specific ontologies that define the meaning and interrelationships of data elements within the food supply chain, ensuring consistency and clarity in traceability information (Storoy et al., 2013). These ontologies are crucial for standardizing how traceability data is identified, measured, and interpreted across different systems and stakeholders. By using a common set of definitions and relationships, the framework facilitates interoperability and accurate communication between diverse traceability systems, overcoming the challenges posed by proprietary formats. The use of ontologies also supports the integration of advanced technologies, such as automated data collection and real-time monitoring, enhancing the efficiency and reliability of food traceability. For our research, this developed ontology provided a reference for creating a similar structured, interoperable, and semantic-based traceability ontology applicable to animal traceability systems and ensuring accurate and standardized data exchange.

The Food Track & Trace Ontology (FTTO) was developed to manage food traceability across the supply chain, integrating key elements such as actors, food products, service products, and processes (Pizzuti et al., 2014). The ontology is part of a global system to enhance traceability, quality, and safety controls from "farm to fork," ensuring the accurate tracking and tracing of food items. FTTO uses standardized terminology and processes to connect disparate information systems, facilitating interoperability and effective communication among supply chain participants. The study demonstrates ontology's applicability through scenarios involving food safety crises, showing its ability to quickly identify sources of contamination. FTTO's modular structure allows for future adaptation and specialization to different food domains, making it a relevant model for enhancing traceability systems and addressing food safety concerns in various contexts.

The MEat Supply Chain Ontology (MESCO) was developed to enhance traceability and safety in the meat supply chain by providing a standardized framework that links all stages, from farming to the final consumer (Pizzuti et al., 2016). This ontology addresses the gaps in traceability systems, which often fail to connect information on food products with the processes and actors involved in their production and transformation. MESCO uses the Web Ontology Language (OWL) and Description Logic (DL) for formal representation and reasoning, facilitating interoperability among different information systems and integrating data from heterogeneous sources. By enabling detailed tracking and querying of meat products, MESCO supports food safety agents in effectively managing food safety incidents and ensuring compliance with traceability regulations. Its relevance to our research lies in its demonstration of how ontological models can improve traceability and safety in complex food supply chains.

Batlajery et al. (2018) introduced an ontology, prFood, designed to capture and assess the risk of contamination throughout the food supply chain. The ontology focuses on modeling food provenance, history, and contamination risk, aligning with EU and UK food safety regulations. prFood integrates existing food ontologies and extends the PROV-O standard to include specific food-related entities, activities, and agents, enabling comprehensive traceability and risk assessment. The mapping procedure between prFood and other food ontologies allows for collaborative risk evaluation and data integration across diverse systems. This research highlights the importance of ontological frameworks in enhancing data transparency, interoperability, and risk management, which is relevant to our research on developing an ontology for monitoring livestock traceability and ensuring food safety.

FoodOn is an ontology designed to improve global food traceability, quality control, and data integration by providing a comprehensive, harmonized vocabulary for describing food items from farm to fork (Dooley et al., 2018). FoodOn addresses the challenge of data silos caused by disparate food terminologies and supports interoperability across various domains, including food safety, quality, production, distribution, and consumer health. FoodOn is relevant to animal traceability as it includes specific terms related to domesticated animal food sources, offering a structured framework to track food origin, processing, and distribution chains. By facilitating consistent data description and integration, FoodOn enhances the ability to monitor and trace food products effectively, aiding in regulatory compliance and food safety efforts. The project leverages existing resources like the LanguaL food classification system and aims to create a shared global standard that aligns with other ontologies for seamless data sharing and analysis.

The Dairy Cattle Performance Ontology (DCPO) serves as a unified framework to manage and analyze complex dairy farming data (Fuentes et al., 2022). This ontology addresses the heterogeneity and complexity of dairy data, such as health, nutrition, yield, and genetics, by providing a standardized vocabulary that supports interoperability and facilitates data integration from various sources. DCPO's relevance to animal traceability research lies in its capacity to enable seamless data exchange and improve the precision of monitoring and decision-making processes in livestock management. By using DCPO, stakeholders can perform more accurate queries and analyses, such as evaluating milk production metrics or assessing genetic potential, which are crucial for effective animal traceability. Additionally, the ontology's application in pattern mining and predictive modeling demonstrates its potential to enhance the understanding of dairy production trends, supporting better management practices and disease prevention.

Ouf (2022) developed an ontology to enhance traceability within the food supply chain, addressing critical phases from raw material extraction to final product distribution. By integrating Semantic Web technologies, this approach aims to improve food safety, quality, and overall supply chain efficiency through better planning, forecasting, and productivity. The proposed ontology covers all food types and stages of the supply chain, which is a significant advancement over existing research that typically focuses on specific food categories or segments. Utilizing tools like OWL and SPARQL, the ontology supports reasoning and knowledge inference, offering a shared understanding among diverse stakeholders. This research is relevant to our work, as it showcases how ontologies can facilitate data integration, semantic mediation, and the enhancement of transparency and traceability across complex supply chain systems.

Allouch et al. (2023) presented an ontology-based framework integrated with Internet of Things (IoT) technologies to enhance the efficiency and safety of food supply chains. This study uses ontologies to create a shared understanding and standardized representation of critical concepts, such as temperature and humidity, enabling real-time monitoring and data exchange among different stakeholders. This semantic modeling facilitates better traceability, ensuring that food quality is maintained throughout storage and transportation by providing accurate and consistent information. The framework supports compliance with food safety regulations, helps in rapid identification and response to potential safety issues, and improves overall transparency. By leveraging ontologies, the framework aims to enhance coordination, reduce operational costs, and boost consumer trust in the food supply chain.

Hemnil et al. (2023) developed an ontology for the UHT milk production process to enhance traceability and quality control throughout the supply chain. By integrating ontology with blockchain technology, the system provides a comprehensive and transparent view of milk production from farm to consumer, facilitating knowledge exchange and ensuring compliance with food safety standards. The ontology was designed using the Hozo-Ontology Editor, focusing on defining classes, properties, and relationships pertinent to UHT milk production, such as raw materials, processing methods, packaging, and transportation. The ontology's effectiveness was evaluated based on its ability to accurately retrieve relevant information, demonstrating strong browsing coverage and efficient performance in a semantic search system. This approach aligns with our research focus on using ontologies to model complex processes, providing a structured framework for integrating data and enhancing traceability in supply chains.

Frendi et al. (2024) introduced an ontology-based traceability system to enhance visibility and coordination in interconnected supply chains through technologies like IoT, cloud, and fog computing. While the system is not specifically intended for food supply chains, its focus on standardizing information exchange and monitoring product conditions (e.g., temperature and humidity) makes it highly applicable to the food industry, where quality and safety are critical. The ontology provides a shared language that helps overcome challenges related to semantic differences and data consistency among diverse stakeholders, which is essential for effective traceability. This approach supports real-time tracking and detailed knowledge of product movements, ensuring that information is both timely and accurate. The system's ability to maintain product integrity and optimize resource utilization makes it relevant to our research, particularly in enhancing traceability and safety in food supply chains. The summary of the reviewed traceability ontologies is presented in Table 2.

Table 2. The summary of the reviewed traceability ontologies

S/N	Ontology name	Reference	Application domain	Components	Strengths	Weaknesses
1	Bovlac/Value Go	Magliulo et al. (2013)	Dairy supply chain	Milk characteristics, production processes, product origins	Enhances traceability, integrates ICT tools like RFID and QR codes	Limited to dairy products, not broadly applicable to all livestock traceability
2	TraceFood Framework	Storoy et al. (2013)	Food supply chain	Sector-specific ontologies, data element relationships	Standardizes traceability data, enhances interoperability	General framework, not specifically tailored for animal traceability
3	Food Track & Trace Ontology (FTTO)	Pizzuti et al. (2014)	Food supply chain	Actors, food products, service products, processes	Supports modularity and adaptability to various food domains	Focused on food safety, not livestock traceability
4	MEat Supply Chain Ontology (MESCO)	Pizzuti et al. (2016)	Meat supply chain	Activities, actors, food products, lots, processes, service products	Enhances traceability and safety in the meat supply chain	Specific to meat, not all-inclusive for livestock management
5	prFood	Batlajery et al. (2018)	Food provenance and contamination risk	Food history, contamination risk, provenance	Integrates with existing ontologies, focuses on contamination risk	Primarily safety-focused, less emphasis on comprehensive traceability
6	FoodOn	Dooley et al. (2018)	Global food traceability	Food vocabulary, food classification	Harmonized vocabulary, supports global standards	Broad focus, not specific to livestock traceability
7	Dairy Cattle Performance Ontology (DCPO)	Fuentes et al. (2022)	Dairy farming	Health, nutrition, yield, genetics	Supports predictive modeling, improves decision-making	Focused on dairy, limited scope for other livestock types

S/N	Ontology name	Reference	Application domain	Components	Strengths	Weaknesses
8	Food Supply Chain (FSC) Ontology	Ouf (2022)	Food supply chain	Supply chain stages, relationships, knowledge representation with OWL, reasoning capabilities	Applicable to all food types, enhances semantic mediation	Broad focus, not specific to livestock traceability
9	Outbound Logistics Process-Internet of Things (OLP-IOT)	Allouch et al. (2023)	Food supply chain	IOT4Log for Internet of Things concepts, OLP-Onto for outbound logistics processes and resources, a Space-Time module for spatiotemporal relationships	Support real-time monitoring, improves safety and transparency	Focused on IoT integration, less emphasis on semantic detail
10	UHT Milk Production Ontology	Hemnil et al. (2023)	UHT milk production	Raw materials, processing, transportation	Integrates blockchain for enhanced transparency	Limited to UHT milk production, not applicable to all livestock systems
11	Ontology-Based Traceability System (Onto-Fog/Onto-Cloud)	Frendi et al. (2024)	Interconnected supply chains	IoT, cloud, fog computing	Enhances visibility and coordination, supports real-time tracking	General application, not specific to food or livestock traceability
12	Animal Traceability Ontology (ATO)	Current study	Livestock traceability systems in Botswana	Classes (e.g., cattle, farmer, disease), hierarchical taxonomy, object and data properties, formal axioms, instances for animal traceability	Enhances interoperability, supports real-time data integration, includes robust disease management, scalable for small and large farms, aligns with Botswana's specific livestock practices	Generalizability to other geographical contexts might be limited (not yet investigated), currently focused on cattle only

Identified Research Gaps and Context-Specific Challenges

Many existing ontologies, such as the TraceFood Ontology (Magliulo et al., 2013), the FTTO (Pizzuti et al., 2014), MESCO (Pizzuti et al., 2016), and prFood (Batlajery et al., 2018) lack robust capabilities for real-time data processing. Real-time integration is essential for prompt monitoring and swift responses to food safety incidents and disease outbreaks. The absence of these capabilities in current ontologies hinders the ability to take immediate corrective actions, which is crucial to prevent contamination and control the spread of diseases throughout the supply chain.

Scalability presents another significant challenge for ontologies like FoodOn (Dooley et al., 2018), the DCPO (Fuentes et al., 2022), and UHT milk production ontology (Hemnil et al., 2023). These ontologies often need substantial customization to fit various geographical and operational contexts, making their deployment complex and resource-intensive. Such limitations reduce their effectiveness across global supply chains, which require flexibility and adaptability to diverse conditions and regulatory environments.

Accessibility for small-scale producers, especially in developing countries, is limited by the high technological requirements embedded in ontologies like FTTO (Pizzuti et al., 2014), FoodOn (Dooley et al., 2018), and the UHT milk production ontology (Hemnil et al., 2023). These ontologies typically rely on advanced technological infrastructure, which can be a barrier to adoption among smaller stakeholders. Developing simplified versions or adaptations with lower technological demands could facilitate broader adoption, ensuring more inclusive participation in traceability initiatives.

While some ontologies, such as DCPO (Fuentes et al., 2022), address aspects of dairy health management, others like Bovlac/ValueGo (Magliulo et al., 2013), FTTO (Pizzuti et al., 2014), and MESCO (Pizzuti et al., 2016) lack comprehensive disease management functionalities. Effective animal traceability requires detailed modules for disease monitoring, including prevention, early detection, and response strategies. The absence of these critical features limits the ability of these ontologies to support comprehensive health monitoring and implement biosecurity measures effectively.

These identified gaps underscore the need for future advancements in animal traceability ontologies to focus on enhancing real-time data processing, improving scalability, integrating accessible technologies for small-scale producers, and incorporating robust disease management systems. Addressing these areas will significantly improve the efficiency, inclusivity, and reliability of traceability systems.

In addition to the identified gaps in existing studies on traceability ontologies, our study aimed to address challenges specific to the Botswana context. Botswana's livestock sector faces intertwined challenges of declining cattle populations due to poor management, climate-induced droughts, and systemic inefficiencies, compounded by inadequate traceability systems, limited market access, infrastructure deficits, low technology adoption, and technical literacy, all of which hinder food security, economic sustainability, and compliance with international trade standards. The ATO addresses Botswana's identified challenges by standardizing data representation to improve management practices and decision-making, enabling real-time data sharing for better coordination and response to systemic inefficiencies. It tackles the issue of inadequate traceability systems by enhancing interoperability and integrating disease monitoring, vaccination records, and movement tracking to manage livestock health and reduce mortality rates. Additionally, the ATO supports market compliance by aligning traceability data with international trade standards, while its modular, cost-effective design promotes accessibility for small-scale farmers, addressing infrastructure deficits, low technology adoption, and limited technical literacy.

Proposed Animal Traceability Ontology

The Animal Traceability Ontology (ATO) for Botswana offers improvements over existing ontologies by addressing key gaps in real-time data integration, scalability, accessibility for small-scale producers, comprehensive disease management, and alignment with local practices. Unlike many existing models, ATO is designed to support real-time data processing, allowing immediate updates and timely responses to health issues and disease outbreaks, which is crucial for effective livestock management.

Scalability is another strength of the ATO, with a modular design that accommodates various operational scales, from small farms to large commercial enterprises. This adaptability ensures seamless integration with existing systems and the ability to expand as needed. Furthermore, the ATO emphasizes accessibility, making it practical for small-scale farmers in developing regions by supporting the use of cost-effective technologies, such as mobile applications, to participate in traceability initiatives without requiring significant technological investment.

The ATO also includes robust disease management modules, enabling comprehensive tracking of disease outbreaks, vaccination records, and biosecurity measures. This holistic approach to health management ensures better prevention, detection, and response capabilities, which are essential for maintaining livestock health and complying with regulatory standards.

Tailored specifically for Botswana, the ATO aligns with local practices, regulatory guidelines, and stakeholder needs, making it highly relevant and applicable within the region's livestock industry. By adopting standardization and promoting interoperability, the ATO facilitates seamless data sharing across different systems, enhancing transparency and collaboration among stakeholders. Overall, the ATO provides a more effective, reliable, and inclusive tool for animal traceability, supporting sustainable livestock management and economic development in Botswana.

METHODOLOGY

RESEARCH DESIGN

To develop Animal Traceability Ontology (ATO), this study employed a mixed-methods research design (Creswell & Creswell, 2022). The research combined qualitative and quantitative approaches to gather comprehensive data and insights, ensuring the ontology's effectiveness and applicability. The research process is outlined in Figure 1.

The ontology was developed using insights from both qualitative and quantitative data. The development followed METHONTOLOGY, a well-established methodology for ontology development (Fernandez et al., 1997), detailed in one of the next subsections. Tools like Protégé and Apache Jena Fuseki were utilized to build and query the ontology. The evaluation of the developed ontology was performed using ontology evaluation techniques and tools such as OntoMetrics, SPARQL queries, and Pellet reasoner.

ETHICAL CONSIDERATIONS

Ethical considerations, including informed consent, confidentiality, and compliance with ethical standards, were adhered to throughout the research. The ethical approval for this study was obtained from the Directorate of Research and Development at Botswana International University of Science and Technology (reference HREC-011). The Ministry of Agricultural Development and Food Security (reference DVS 7/4/1 VII (90)) and the Ministry of Communications, Knowledge and Technology (reference MCKT/1/11/1 I (38)) approved the research permits to carry out this study. Participant consent was obtained, and data collection followed ethical guidelines, ensuring transparency and participant protection.

SAMPLING AND DATA COLLECTION

The study participants included farm owners and managers, veterinary representatives, local administrative authority representatives, MoA officials, and Botswana Meat Commission representatives. These stakeholders provided critical insights, experiences, and recommendations aligned with the research questions. Specifically, farm owners and managers shared practices and requirements for animal traceability at the farm level. Veterinary representatives detailed tasks such as disease monitoring, vaccination records, and movement tracking. Local administrative authority representatives contributed information on managing stray cattle and its role in traceability. MoA officials provided insights into the implementation and functionality of BAITS, while Botswana Meat Commission representatives offered details on market systems, cattle tracking, and trade requirements.

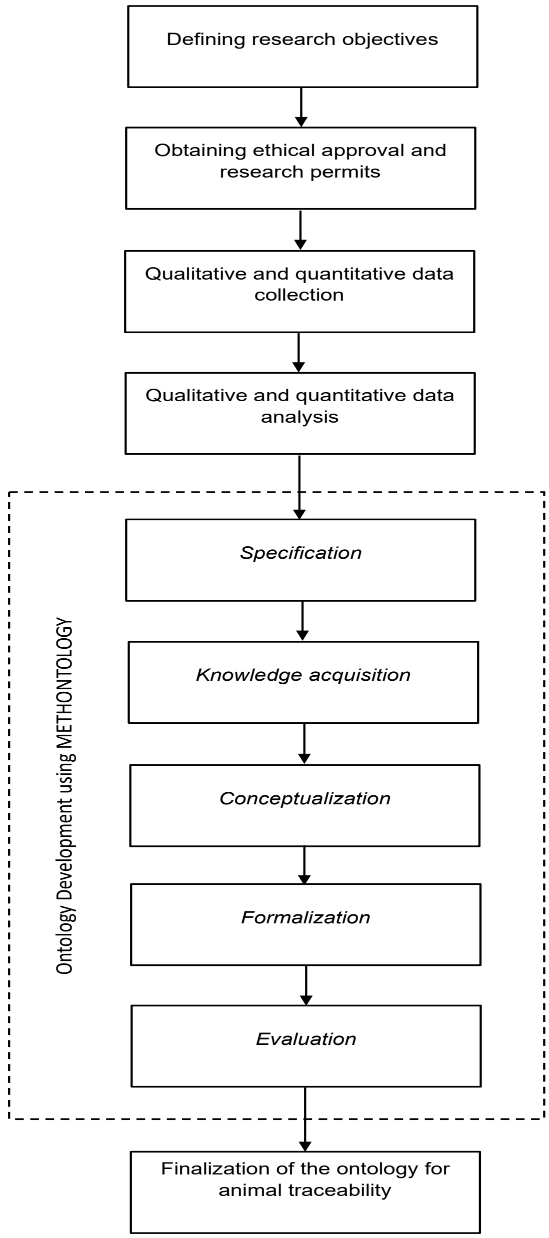

Figure 1. Steps followed to develop the ATO

Purposive sampling, as described by Tongco (2007), was employed to select participants with specific knowledge and willingness to provide reflective and articulate feedback. This method, suitable for both qualitative and quantitative research, aligned with the study's objective of gathering relevant data from informed stakeholders. Botswana's nine districts served as strata for sampling. Government veterinary officials provided farmer lists for random selection in some districts, while direct field visits facilitated farmer selection in areas lacking such lists.

The sample size determination was guided by literature on data saturation for mixed-method research. Hennink and Kaiser (2022) emphasize that code saturation can often be achieved with fewer interviews, while thematic saturation requires larger samples to understand complex issues fully. Guest et al. (2006) found that thematic saturation occurred within the first 12 interviews, with basic elements for meta-themes present as early as six interviews (i.e., code saturation). Creswell and Guetterman (2018) recommend interviewing 20 to 30 participants for qualitative studies to ensure comprehensive data collection. This study included 60 participants, combining interviews for qualitative data and questionnaires for quantitative data. This ensured alignment with the study's objectives and relevant sampling recommendations.

To ensure validity and reliability, interview and questionnaire tools underwent peer and expert reviews by postgraduates, academic staff, and professionals in ontology and traceability. Pilot interviews were conducted to test the tools, and revisions were made based on feedback.

DATA ANALYSIS

The quantitative analysis included descriptive statistics to analyze questionnaire data and gather quantitative insights. In analyzing qualitative data, thematic analysis was utilized to identify key themes, concepts, and relationships from the interviews, focus groups, and document analysis.

The coding process in this study followed a systematic approach to ensure transparency, reliability, and validity, utilizing both manual and computer-assisted techniques. This integration of manual and software-based coding aligns with the study by Al-Adwan and Sammour (2021).

In the first step, manual coding was guided by the two-cycle coding process outlined by Saldana (2021). In the first cycle, magnitude and in-vivo coding were employed to generate initial codes directly from the raw data, capturing the essence of participant responses. Eclectic coding was used as an intermediary step to refine the initial codes before transitioning to the second cycle. During the second cycle, evaluation coding was applied to group-related codes into categories that aligned with the study's objectives.

After completing the manual coding, data was imported into NVivo 12 to leverage its organizational and visualization capabilities. Initial nodes were created in the software to represent the manually coded data. Nodes and sub-nodes were developed to reflect themes and sub-themes, ensuring the software mirrored the conceptual organization established during manual coding. The coding stripes and node hierarchy functions in NVivo 12 facilitated visual tracking of coded segments and thematic relationships.

To enhance the reliability of the coding process, double coding was implemented on a subset of the data. This involved an independent reviewer recoding portions of the data to verify consistency in the coding scheme. Discrepancies were resolved through discussions to reach a consensus, improving inter-coder agreement. Additionally, the coding framework was refined iteratively by testing against new data segments, ensuring its adaptability and robustness. The implementation of double-coding and iterative refinement of the coding framework parallels the methodological rigor described by Al-Adwan and Sammour (2021).

The use of NVivo enabled systematic query generation, associating data with respondents and their districts. This functionality allowed the study to explore thematic patterns, relationships, and emerging trends across various stakeholder responses. The final set of themes was categorized into concepts that directly informed the development of the ontology-driven framework.

By integrating manual coding with NVivo's advanced features, this study ensured that the coding process was both thorough and adaptable. The combination of cycles, rigorous review, and software-supported organization enhanced the credibility of the thematic analysis, directly contributing to the study's findings and recommendations.

APPLYING METHONTOLOGY TO DEVELOPING THE ANIMAL TRACEABILITY ONTOLOGY

A widely adopted methodology for ontology development, METHONTOLOGY (Fernandez et al., 1997), was employed in this research to systematically create an Animal Traceability Ontology for

Botswana. The METHONTOLOGY approach provided a structured and iterative process, ensuring that the ontology was robust, scalable, and capable of supporting the complex requirements of animal traceability. The research was conducted in six phases as outlined by the METHONTOLOGY approach, namely (1) specification, (2) knowledge acquisition, (3) conceptualization, (4) formalization, and (5) evaluation (Figure 1).

In the first phase, specification, the purpose, goals, boundaries, and scope of the ontology were identified. This phase involved detailed planning, where tasks were organized based on the time and resources required. Specification played a crucial role, gathering insights through interviews, focus groups, and questionnaires with key stakeholders such as farmers, veterinary officers, and other relevant experts in the field of animal traceability. This ensured that the ontology was designed to meet the specific needs and challenges of the stakeholders involved.

The knowledge acquisition phase involved acquiring knowledge from stakeholder experts in animal traceability, with the objective of animal identification and traceability automatic ontology learning. The knowledge acquisition relied on two primary sources: literature and models from relevant literature, as well as collected data. Data collection was carried out using interviews and questionnaires targeted at key animal traceability stakeholders, including farmers, veterinary officers, Matimela (the management of stray cattle – Setswana) officers, representatives of Botswana Meat Commission, officers from the Ministry of Agricultural Development and Food Security, and Botswana Animal Identification and Traceability System (BAITS) agents. This methodology focused on extracting animal identification, traceability, and tracking concepts that are common within the animal traceability domain from multiple sources. The process involved identifying relevant attributes, relationships, and constraints, which were then organized into a structured format.

In the conceptualization phase, the knowledge acquired during the previous phase was systematically organized into a conceptual model. This involved creating models to represent the relationships and hierarchies within the animal traceability domain. The process included defining entities such as “farmer,” “cattle,” “farm location,” and “veterinary services” and delineating their relationships. A hierarchical taxonomy was developed, categorizing various classes like “animal,” “person,” “device,” and “event.” Subclasses and attributes were specified to capture detailed information, including cattle identification and health status. The process of developing the ontology also included defining object properties and data properties to link different classes, ensuring the ontology could facilitate data sharing across diverse systems. Additionally, alignment with existing standards and best practices was considered to ensure compatibility and interoperability with other animal traceability systems, which involved adopting standard naming conventions and data representation formats.

The formalization phase involved converting the conceptual model into a semi-computable format using Protégé 5.6.1 in the OWL language. The Pellet reasoner was utilized within Protégé to ensure logical consistency, equivalence, and valid instantiation of the ontology. Visualization tools like OWLViz and OntoGraf provided graphical representations, highlighting the hierarchical structure and interrelationships of the ontology’s classes and subclasses. The development process systematically organized entities into an inheritance hierarchy, defined object properties to link different entities, and assigned data properties to capture specific attributes. Individual instances were created for each class, and appropriate relationships and attributes were assigned to these individuals, ensuring that the ontology accurately modeled the animal traceability domain.

Finally, the evaluation phase ensured that the ontology met the desired quality and performance standards. Due to its importance, the methodology for evaluation of the ontology is considered in a separate subsection.

Methodology for the Ontology Evaluation

The evaluation of the ontology was conducted using a multi-faceted approach that incorporated structural, functional, and usability profiling evaluations, as well as comparative analysis. This approach aimed to ensure the ontology's robustness, consistency, and practical applicability.

The structural evaluation involved the use of schema and graph metrics to analyze the ontology's structure. The OntoMetrics web-based tool was employed for this purpose (https://ontometrics.informatik.uni-rostock.de/ontologymetrics). Schema metrics such as inheritance richness (IR), relationship richness (RR), and class/relation ratio (CRR) were calculated (Tartir et al., 2010). IR measures the distribution of knowledge across ontology by calculating the average number of subclasses per class. RR assesses the diversity of relationship types within the ontology. CRR evaluates the ratio of classes to relationships within the ontology. These metrics helped in understanding the distribution of knowledge across ontology. Graph metrics, including depth, breadth, and cardinality, were computed to examine the topological dimensions and logical structure of the ontology. These metrics provided insights into ontology's adequacy and reliability, confirming its ability to represent complex relationships and knowledge structures effectively.

Tools used in the functional evaluation included Apache Jena Fuseki and the Pellet reasoner. These tools were utilized to assess the ontology's functionality. Apache Jena Fuseki was used to run SPARQL queries, which validated the ontology's capability to handle specific tasks and queries accurately. The efficient execution of these queries indicated the ontology's alignment with its intended functionality, demonstrating its performance in practical scenarios. The Pellet reasoner was employed to ensure the ontology's consistency by checking for any contradictions. Consistency checks were vital for maintaining the reliability and interoperability of the ontology, ensuring that the facts deduced did not conflict with each other.

Usability profiling evaluation involved analyzing class axioms, object properties, and data properties using OntoMetrics (https://ontometrics.informatik.uni-rostock.de/ontologymetrics). This evaluation assessed the relevance and completeness of the ontology, focusing on the distribution of instances across different classes and the richness of object and data properties. In addition to that, pragmatic dimensions were evaluated. This evaluation emphasized relevance (how well the ontology met stakeholders' needs) and completeness (coverage of the domain of interest). These dimensions were essential for confirming the ontology's practical utility and adaptability to real-world applications.

The developed Animal Traceability Ontology was compared against a reference ontology, namely the Animal Health Ontology (AHO) maintained by the Swedish National Veterinary Institute (http://datadrivensurveillance.org/animal-health-ontology-aho/). The comparative analysis focused on metrics like class richness and knowledge representation.

Results and Discussion

Results and Discussion of the Specification Phase

In the specification phase, the purpose, goals, boundaries, and scope of the ontology were defined. This phase aimed to ensure a clear understanding of the ontology's requirements, thereby avoiding inconsistencies among its classes. Defining these elements was crucial for maintaining consistency and coherence within the ontology.

The purpose of the ATO was to address the challenges associated with non-interoperable animal traceability systems in Botswana. The goals of the ATO were identified as follows: (1) to enhance interoperability between different stakeholders involved in animal traceability, (2) to standardize vocabularies and data management practices among stakeholders, (3) to enable seamless data integration and exchange, (4) to derive value from traceability data for knowledge-driven economic opportunities, and (5) to support effective knowledge management for accurate and rich data about animal traceability.

The boundaries of the ATO were defined by its focus on representing knowledge directly related to animal traceability, excluding unrelated areas such as non-animal agricultural products or broader environmental concerns. The ATO's scope encompassed enhancing knowledge representation and extraction, promoting reusability, and supporting cross-platform data sharing among various stakeholders involved in animal traceability. These stakeholders included entities involved in the lifecycle of cattle, such as farmers, veterinary services, Matimela officers, the Botswana Meat Commission, the Ministry of Agricultural Development and Food Security, law enforcement agencies, and the public.

The ATO was envisioned to be part of a high-level, ontology-driven framework that would integrate seamlessly with developer applications and software. It was designed to be versatile, allowing it to be implemented across diverse animal traceability platforms, ensuring effective and up-to-date monitoring and tracking of cattle. This capability underscored the ATO's potential to meet the varying needs of different stakeholders involved in animal traceability, thereby enhancing the overall effectiveness and efficiency of livestock management systems.

Results and Discussion of the Knowledge Acquisition Phase

The knowledge acquisition phase gathered information that is essential for developing the ATO. Data obtained from interviews, focus groups, and document analysis provided insights into existing practices, stakeholder needs, regulatory guidelines, and best practices in animal traceability. This phase led to the creation of a comprehensive glossary of terms related to animal traceability, which included key concepts such as "cattle," "farm location," "veterinarian," "tracking," and "traceability." Insights from stakeholders' real-world experiences helped refine the ontology requirements, ensuring the developed ontology accurately reflects the practices and needs of various stakeholders involved in animal traceability in Botswana.

Results and Discussion of the Conceptualization Phase

In the conceptualization phase, the primary objective was to organize and structure the acquired knowledge into a coherent and systematic format that would facilitate the development of Animal Traceability Ontology. This process utilized graph-based and tabular notations to transition from informal data to semi-formal specifications. The phase began by building a glossary of terms, which included defining and describing relevant concepts, instances, and attributes pertinent to the animal traceability domain. Terms such as "cattle," "farm employee," "veterinarian," "traceability," "tracking," and "vaccination" were identified and listed in a glossary table, providing clear definitions and synonyms to standardize the terminology used throughout the ontology development. The glossary of terms for the ATO is available at Figshare (https://figshare.com/articles/dataset/Animal_Traceability_Ontology_ATO_for_Botswana/26826700?file=48765313).

Next, the development of concept taxonomies was carried out to classify these terms into hierarchical structures. The taxonomy categorized various classes such as "animal," "person," "device," and "event" and further defined their subclasses and specific attributes. For example, the "cattle" class included attributes like ID, ear tag number, breed, and location, while the "farmer" class comprised attributes like national identity number, address, and contact information. The creation of taxonomy provided a visual representation of the relationships among different concepts, illustrating how entities like "farmer," "cattle," "farm location," and "veterinary services" are interconnected within the animal traceability system. The resulting taxonomy is shown in Figure 2.

Following the establishment of taxonomies, ad hoc binary relations were developed to map the interrelationships between concepts, enhancing the understanding of how different entities interact within the ATO. These relationships included associations such as "farmer employs manager," "cattle tracked by tracking device," and "veterinarian administers vaccination." The graphical representation of these binary relations, illustrating the complex web of interactions that characterize the animal traceability domain, is available in Figshare (https://figshare.com/articles/dataset/Animal_Traceability_Ontology_ATO_for_Botswana/26826700?file=48765319).

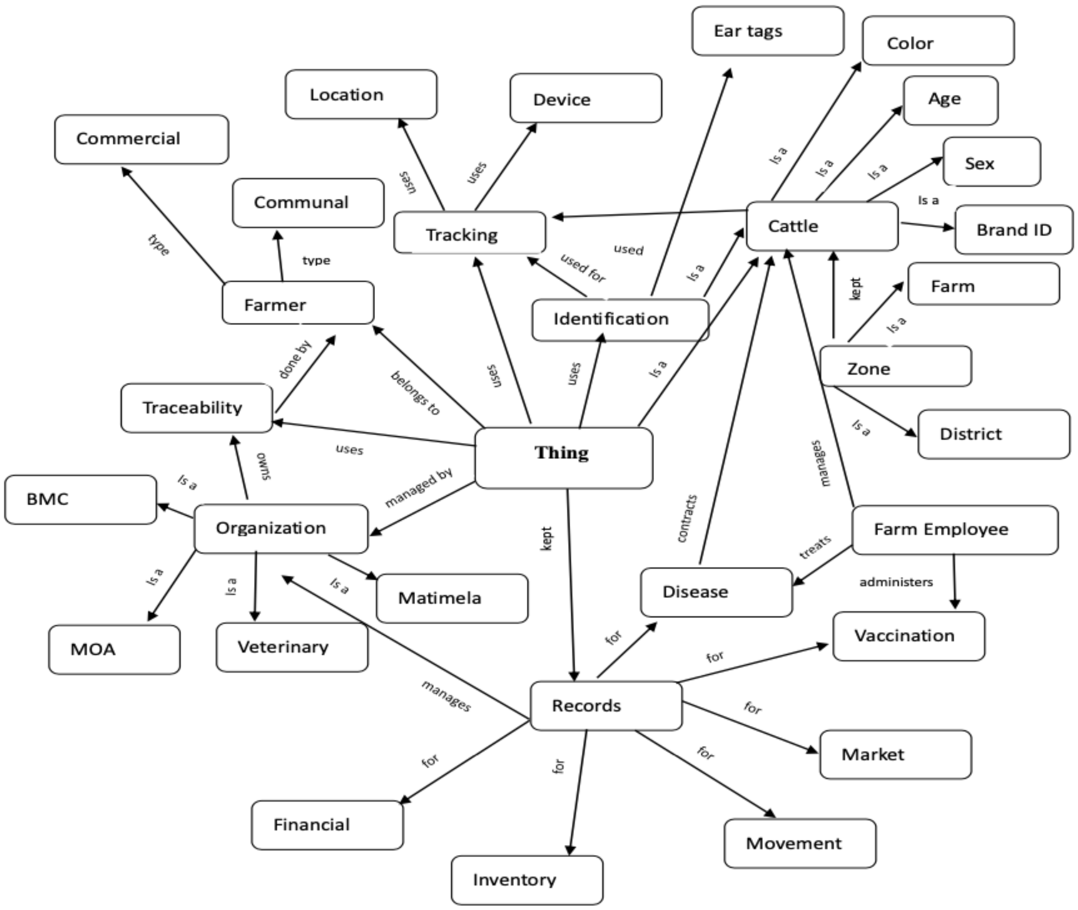

Figure 2. The animal traceability taxonomy

The concept dictionary was built upon identified ad hoc binary relations by defining the properties, instances, and relationships of each concept within the animal traceability taxonomy. This included a detailed listing of domain concepts, attributes, and relationships, ensuring a comprehensive understanding of each concept's role and interaction. The ad hoc binary relations were then merged to create a relational table that illustrated the connections between concepts, specifying relation names, sources, targets, and inverse relations. Additionally, instance attributes were described in detail, outlining the specific fields, value types, and value ranges for each attribute to ensure precision in the ontology's representation. The class attributes were also meticulously defined, identifying key attributes relevant to various concepts like "farmer," "traceability," and "vaccination." The extracts from the concept dictionary, relational table, instance attributes table, and class attribute table are available in Figshare (https://figshare.com/articles/dataset/Animal_Traceability_Ontology_ATO_for_Botswana/26826700?file=48765307).

The conceptualization phase also involved describing formal axioms to define logical expressions that are universally true within the ontology. These axioms helped ensure consistency and accuracy in the representation of knowledge. Examples of formal axioms included statements like "a farmer that owns cattle also registers for traceability" and "traceability can locate disease and farm." The table presenting formal axioms is available in Figshare (https://figshare.com/articles/dataset/Animal_Traceability_Ontology_ATO_for_Botswana/26826700?file=48765310).

The final step detailed relevant instances from the concept dictionary, with each instance table specifying the concept name, instance names, attributes, and their corresponding values. An example of the instance description table for the instance of the "farmer" concept, which includes attributes like national ID number, full name, address, contacts, etc., is available on Figshare (https://figshare.com/articles/dataset/Animal_Traceability_Ontology_ATO_for_Botswana/26826700?file=48765316).

Overall, the conceptualization phase successfully transformed the acquired knowledge into a structured and systematic representation. By defining a comprehensive glossary, establishing taxonomies, mapping binary relations, and developing a concept dictionary, the phase laid a solid foundation for the subsequent development and implementation of the ATO. This structured approach ensured that ontology would accurately reflect the complexities of animal traceability, facilitate data sharing and interoperability, and support effective tracking and monitoring practices within the domain.

Results and Discussion of the Formalization Phase

The formalization process effectively transformed the conceptual model into a structured and computable ontology. This transformation was achieved using the Protégé 5.6.1 tool and the OWL language, ensuring that the ontology was both rigorous and versatile. Throughout the development, the ontology reasoner, Pellet, was employed for consistency checking, equivalence checking, and instantiation checking, validating the ontology's logical structure. The successful implementation of these checks ensured that the relationships and properties within the ontology were logically sound and free of inconsistencies.

The creation of classes and subclasses in Protégé involved organizing the ATO into a hierarchical structure under the root class owl:Thing. This included defining the superclass "cattle," with subclasses such as "identification" and further sub-subclasses like "earTag," providing detailed and refined information about the main class. All identified classes and subclasses from the conceptualization stage were arranged into this inheritance hierarchy, as shown in Figure 3. This figure displays the complete list of classes, subclasses, and sub-subclasses, which is crucial for understanding the hierarchical organization of the ontology.

The creation of object properties in Protégé defined the associations between entities within the ATO, linking concepts through various types of specified relationships, as depicted in Figure 4.

The creation of data properties in Protégé involved defining specific attributes under each class in the ATO, such as "firstname," "lastname," "age," and "gender," ensuring ease of understanding and use. These properties were organized by associating them with relevant classes, like "farmer" or "employee," depending on their applicability. Following this, individuals were created within each class, representing specific instances that adhered to predefined constraints, such as diseases under the "disease" class. These individuals were then linked with relevant data and object properties, establishing relationships and defining details such as attributes and roles connected to other classes and individuals within the ontology. The complete ATO is available in Figshare (https://figshare.com/articles/dataset/AnimalTraceability_rdfAnimal_Traceability_Ontology/24461224?file=42977926).

Visualization of the ATO with Protégé OWLViz, depicted in Figure 5, provides a comprehensive graphical representation of the ontology, including a detailed hierarchy of classes, subclasses, and sub-subclasses. For example, the "market" class was depicted with its associated subclasses "local" and "international," which were further divided into categories such as "public," "EU," "feedlot," "regulations," and "others." This visualization demonstrates how all classes and subclasses are organized under the root class owl:Thing, emphasizing the structured and hierarchical nature of the ontology. By visually representing these relationships, OWLViz facilitates understanding how various entities within the animal traceability domain are interrelated.

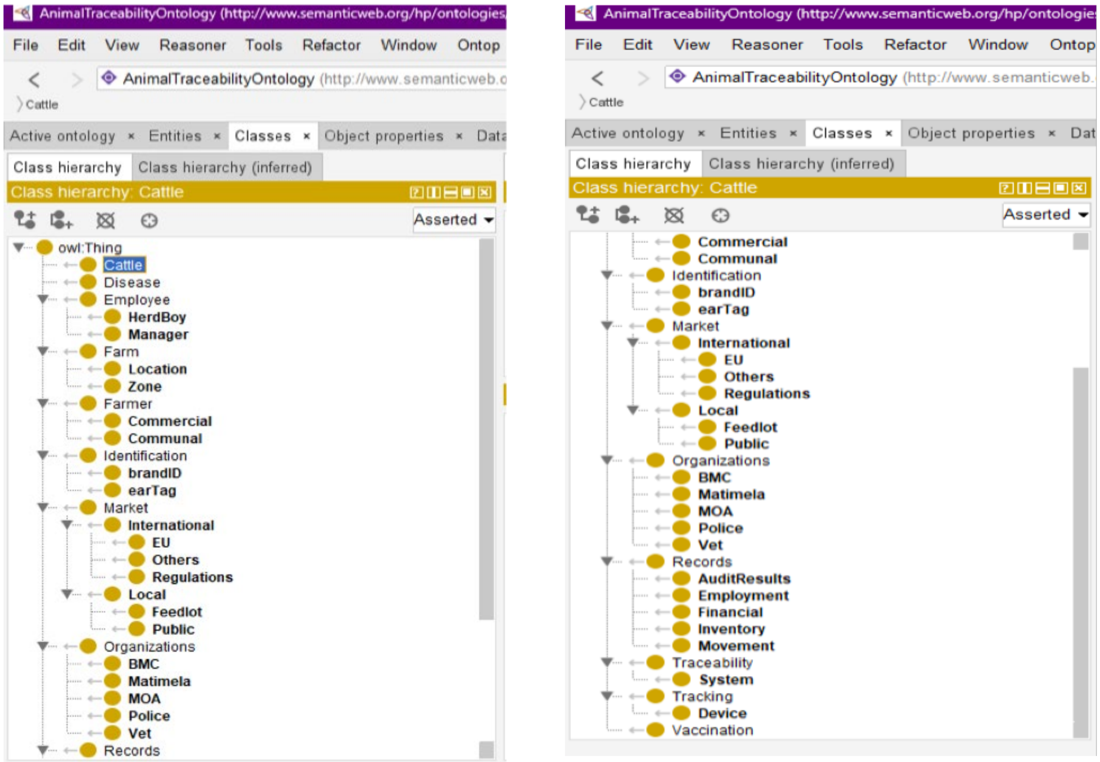

Figure 3. The ATO classes, sub-classes, and sub-sub-classes

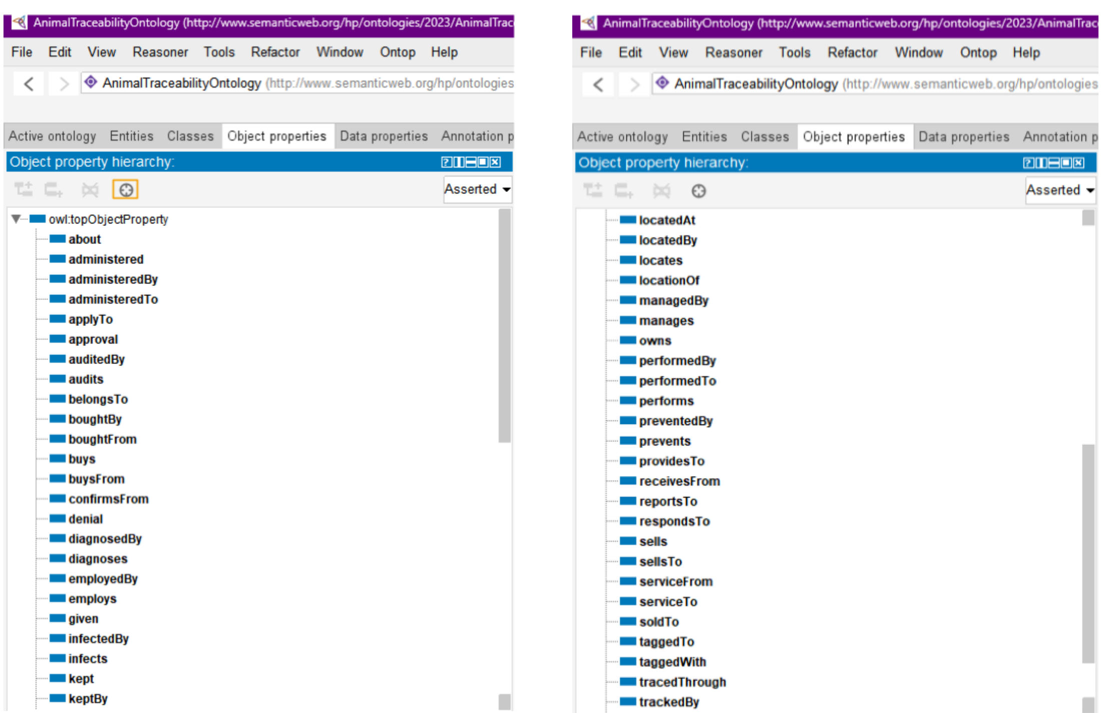

Figure 4. The ATO object properties

Figure 5. Visualization of the ATO with Protégé OWLViz

Visualization with Protégé OntoGraf, illustrated in Figure 6, provided additional insights by mapping out the interrelationships among different classes using dotted arrows to show connections. These visual indicators of relationships demonstrated how individual components, such as "cattle," "farmer," "veterinarian," and "traceability," interacted within the overall system to achieve a unified approach to animal traceability. The OntoGraf tool highlighted the interconnectedness of these components, showing that although each class was developed individually, they were designed to work together seamlessly to support the comprehensive tracking and management of animal-related data.

The use of both OWLViz and OntoGraf ensured a robust visualization of the ontology's structure and interrelations, making it easier for developers, researchers, and stakeholders to comprehend and utilize the ontology. These visual tools not only demonstrate hierarchy and relationships but also validate the ontology's consistency and completeness, ensuring its reliability for practical applications.

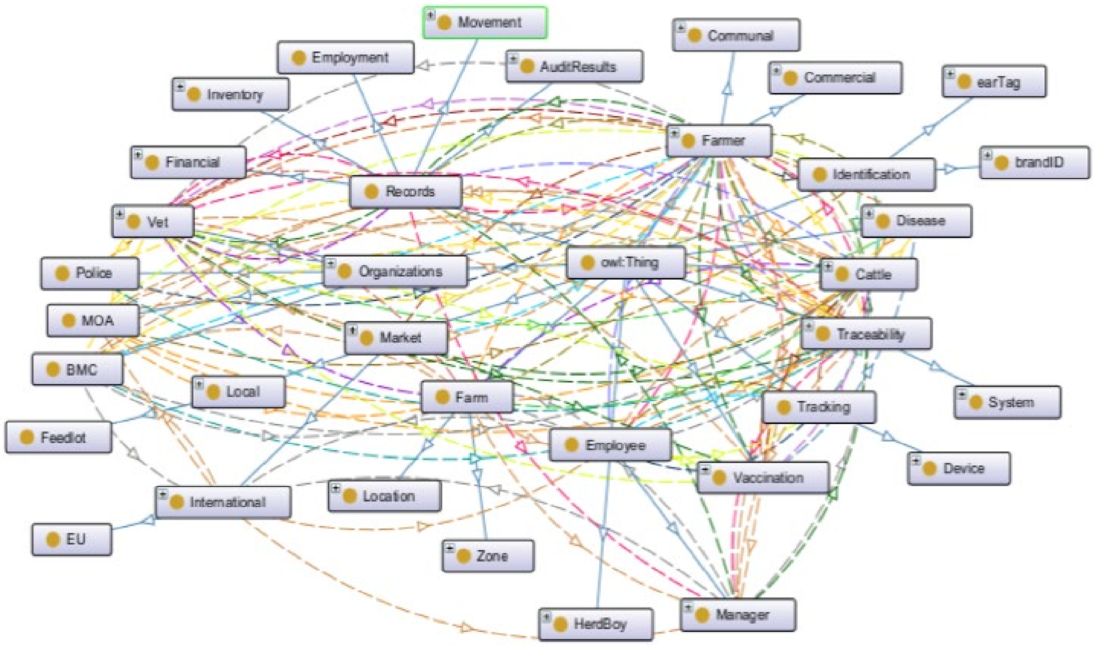

Figure 6. Visualization of the ATO with Protégé OntoGraf

Results and Discussion of the Evaluation Phase

The evaluation of the ATO focused on three main criteria: structural, usability profiling, and functional measurements. In addition to that, a comparative analysis with the reference ontology, AHO (http://datadrivensurveillance.org/animal-health-ontology-aho/), using the same three criteria, was performed.

Structural evaluation results

The structural evaluation of the ATO focused on analyzing its formal semantics and syntax to ensure logical adequacy and overall quality. This evaluation was conducted using the OntoMetrics tool (https://ontometrics.informatik.uni-rostock.de/ontologymetrics), which provided automatic computation of various metrics crucial for assessing the structural aspects of ontologies, including inheritance richness, relationship richness, and class/relation ratios. Additional metrics offered insights into the topology of the ontology's graph structure, including its breadth, depth, and connectivity.

The values calculated using schema metrics were as follows. The IR was found to be 0.692308, indicating a vertically structured ontology with detailed knowledge. This low IR suggests that the ATO is optimized for precise data representation, making it suitable for specialized traceability tasks that require detailed information, thereby enhancing interoperability among stakeholder systems. A higher RR value implies a richer and more interconnected ontology. The ATO's RR was found to be 0.678571, which is close to 1, indicating a diverse set of relationships beyond simple class-subclass hierarchies. This level of richness facilitates robust connections and interactions among different entities within ontology, making the ATO highly interoperable and effective in representing complex traceability scenarios. The CRR was calculated to be 0.464286, suggesting a balanced approach to class definitions and relationships. This indicates medium coverage of descriptive names, meaning the ontology effectively maintains clarity and detail in defining class relations, ensuring an accurate representation of animal traceability processes.

The graph metrics showed an average depth of 1.820513 and a total breadth of 54, with a maximal breadth of 12. The depth indicated a well-defined hierarchical structure, supporting complex relationships, while the breadth reflected moderate horizontal expansion, ensuring comprehensive coverage of various traceability aspects. The absolute root cardinality of the ATO was 12, with 28 leaf nodes and 39 sibling nodes, indicating a robust and well-connected ontology. The graph's fan-outness, calculated at 0.717949 for leaf nodes and 1.0 for sibling nodes, demonstrates effective dispersion of information, ensuring comprehensive coverage and efficient navigation within the ontology. In terms of the path metrics, the ATO's graph contained 39 distinct paths, with an average of 13 paths per graph, illustrating a well-structured topology that supported efficient data retrieval and logical inference. This structure is beneficial for applications that require precise data extraction and processing, reinforcing the ontology's suitability for real-world traceability systems.

Usability profiling evaluation results

Usability profiling for the ATO evaluated its practical application and effectiveness based on its development and use context. The evaluation focused on relevance and completeness, ensuring the ontology meets stakeholder requirements and adequately covers its domain of interest.

The ATO's relevance was confirmed by its alignment with specific stakeholder requirements identified during the development phase. These requirements were used to define the ontology's classes, object properties, and data properties. Completeness was demonstrated by ontology's ability to cover the full scope of animal traceability, encompassing various entities such as animals, farms, veterinarians, and traceability events. This comprehensive coverage ensured that all necessary data and relationships were represented, facilitating accurate tracking and management of animal traceability.

In terms of class and property metrics, the ATO included a central class structure organized under the primary class "Thing," with 27 subclass axioms and four disjoint classes, highlighting its ability to manage distinct concepts within the domain. Object properties in the ontology define relationships between different individuals, while data properties link individuals to specific data values. The ATO comprised 71 object property domain axioms and 72 object property range axioms, demonstrating its capability to manage complex relationships effectively. Additionally, with 96 sub-data property axioms and 120 domain axioms, the ontology provided a detailed framework for data representation and interaction.

Functional evaluation results

The functional evaluation of the ATO focused on assessing its quality based on performance and task execution, using various tools such as the Pellet reasoner, knowledge metrics, and Apache Jena Fuseki.

The ATO's consistency was evaluated using the Pellet reasoner plugin in Protégé. This tool helped identify and rectify inconsistencies in the ontology's development, ensuring logical coherence and semantic agreement between entities. The successful detection and correction of inconsistencies confirmed the ontology's quality and reliability, enhancing its suitability for interoperability.

Furthermore, the ATO was evaluated for its knowledge representation capabilities. The average population (AP) metric, calculated as 3.025641, indicated that data was adequately distributed across the ontology's classes, reflecting a satisfactory level of real-world knowledge representation. The class richness (CR) metric, at 0.487179, suggested moderate coverage of schema knowledge with room for improvement. These metrics affirm that the ATO effectively captures domain-specific knowledge, which is crucial for its practical application in traceability systems.

Functional evaluation using Apache Jena Fuseki involved executing SPARQL queries on a triple-store database, demonstrating high efficiency and accuracy. Real values obtained during the study included average query execution times of around 50-100 milliseconds for simple queries and 200-300 milliseconds for more complex ones, showcasing rapid response times. For instance, a query to retrieve an employee of a specific farmer returned "herdboy1" accurately, while a query for the farm name associated with a farmer correctly returned "Sandveld." These results illustrate the ATO's ability to handle real-time data retrieval and processing effectively, which is crucial for practical applications in animal traceability. The ontology's performance confirms its scalability and suitability for high-demand environments, ensuring reliable data access for stakeholders monitoring livestock health, ownership, and movement.

Comparative analysis with reference Animal Health Ontology (AHO)

The evaluation included a comparative analysis between the developed Animal Traceability Ontology and the reference Animal Health Ontology (AHO) to assess interoperability and alignment with established standards.

The structural comparison of the two ontologies demonstrated that in terms of inheritance richness (IR), the ATO showed a value of 0.692308, reflecting a vertically detailed knowledge structure, which enhances precise data integration and interoperability for specific systems. In contrast, the AHO had a lower IR value of 0.25, indicating a more general knowledge structure. This suggests that while the AHO may support broader applicability across different domains, it might not provide the same level of detail required for specialized animal traceability purposes.

The relationship richness (RR) for the ATO was 0.678571, which is closer to 1, demonstrating a rich network of diverse relationships beyond simple class-subclass hierarchies. In comparison, AHO had a lower RR value, closer to zero, indicating a more limited use of non-inheritance relationships. This disparity suggests that the ATO may offer more comprehensive semantic connections, making it more effective for complex data modeling scenarios required in animal traceability.

A usability profiling comparison was performed to evaluate both ontologies' relevance and completeness. The ATO had a fair coverage of descriptive names, supported by its class richness and average population metrics, which align well with specific stakeholder requirements for animal traceability. In contrast, the AHO showed a higher class/relation ratio (CRR), indicating potential issues with the descriptive accuracy of class names. This suggests that the ATO may provide more precise and relevant information for its intended domain compared to the AHO.

The functional comparison using SPARQL queries and the Pellet reasoner demonstrated that the ATO maintained consistency and could accurately perform specific data retrieval tasks. Both ontologies showed reliability in handling SPARQL queries, but the ATO demonstrated a higher degree of specificity in querying detailed information about farmers, employees, and farms. This specificity highlights its tailored design for precise animal traceability applications, whereas AHO, being more general, might not cater to such detailed requirements. The results of the comparison of the two ontologies are presented in Table 3.

Table 3. Comparison of the ATO and AHO

Category	ATO	AHO
Inheritance Richness (IR)	0.692308, indicating a vertically detailed knowledge structure for enhanced data integration and interoperability	0.25, reflecting a general knowledge structure suitable for broader applicability but less specialized use
Relationship Richness (RR)	0.678571, demonstrating a rich network of diverse relationships beyond simple class-subclass hierarchies	Lower RR value, suggesting limited use of non-inheritance relationships and less semantic connection diversity
Class/Relation Ratio (CRR)	Fair coverage of descriptive names, aligning well with stakeholder requirements for animal traceability	Higher CRR, indicating potential issues with the descriptive accuracy of class names, less suited for traceability

Category	ATO	AHO
Usability Profiling	Provides precise and relevant information for animal traceability through fair coverage of descriptive names and class richness	Broader scope but less precise for traceability applications due to generality and potential descriptive issues
SPARQL Query Performance	Maintains consistency and high specificity in querying detailed information about farmers, employees, and farms	Reliable for general SPARQL queries but lacks the specificity required for detailed animal traceability tasks
Domain Focus	Tailored design ensures focused domain relevance, making it effective for precise animal traceability applications	Broader applicability across domains but not optimized for specialized animal traceability purposes
Alignment with Standards	Ensures better data integration, semantic clarity, and functionality in animal traceability systems	Offers general support for interoperability but may require customization for specialized applications

The comparative analysis, therefore, revealed that the ATO, with its detailed structure, rich relationship network, and focused domain relevance, outperforms the AHO in specialized applications like animal traceability. While AHO offers a broader scope, the specific and consistent design of the ATO ensures better alignment with traceability requirements, providing more effective data integration, semantic clarity, and functionality in animal traceability systems.

CONCLUSION

RESEARCH CONTRIBUTION

This paper presents the development of the Animal Traceability Ontology (ATO) specifically tailored for livestock monitoring in Botswana. The ATO addresses the country's intertwined challenges of declining cattle populations due to poor management, climate-induced droughts, and systemic inefficiencies. The ATO responds to these issues by standardizing data representation, a key step in tackling inadequate traceability systems and enhancing management practices and decision-making. Additionally, it enables real-time data sharing for better coordination among stakeholders, addressing systemic inefficiencies that hinder food security, economic sustainability, and compliance with international trade standards.

The ATO leverages METHONTOLOGY, a structured approach to ontology development, ensuring robust and scalable integration of traceability data across stakeholders, which is critical in overcoming infrastructure deficits, low technology adoption, and limited technical literacy prevalent in Botswana's livestock sector. By incorporating features like enhanced interoperability and the integration of disease monitoring, vaccination records, and movement tracking, the ontology improves livestock health management, reduces mortality rates, and ensures compliance with international trade standards.

The implementation and evaluation of the ATO using tools such as Protégé and Apache Jena Fuseki demonstrate its potential to improve traceability practices, which directly addresses Botswana's limited market access and systemic inefficiencies. The ATO supports small-scale farmers by aligning traceability data with international trade standards and offering a modular, cost-effective design, mitigating barriers like infrastructure deficits and low technical literacy. This approach facilitates informed decision-making, enhances trade compliance, and promotes knowledge-driven economic opportunities within the livestock sector, ultimately contributing to improved food security and economic sustainability in Botswana.

Practical Implications and Implementation Strategies for the ATO

The ATO presents an opportunity to transform Botswana's animal husbandry sector by addressing critical challenges such as data heterogeneity, limited interoperability, and inadequate disease management. The findings of this study underscore the need for practical and actionable strategies to implement the ATO effectively, ensuring its adoption and long-term sustainability within the livestock industry.

One of the most immediate implications of the ATO is its potential to enhance collaboration among stakeholders. By standardizing data representation, the ontology facilitates seamless communication and coordination between key players, including farmers, veterinary officers, and the Botswana Meat Commission. To achieve this, the Ministry of Agriculture and Lands of Botswana should integrate diverse systems under a unified framework supported by training programs and workshops to ensure stakeholders are well-equipped to adopt the new system.

The integration of the ATO with the existing Botswana Animal Identification and Traceability System (BAITS) is a strategic step that can leverage the current infrastructure to reduce implementation costs. Drawing from the success of established ontology-based frameworks, this integration should focus on developing application programming interfaces (APIs) and middleware to ensure interoperability between BAITS and the ontology-driven platform. This alignment can streamline data management, improve accuracy, and enable real-time decision-making across the livestock sector.

Real-time data integration is a critical feature of the ATO, enabling prompt responses to disease outbreaks and compliance with international trade regulations. The study's validation of tools such as Apache Jena Fuseki and SPARQL queries highlights their capability to support live data querying and monitoring, which are essential for ensuring timely interventions in disease management and trade-related activities. These functionalities can position Botswana as a leader in implementing advanced traceability technologies within the region.

Small-scale farmers, who form the backbone of Botswana's livestock industry, stand to benefit from the ATO's accessibility-focused design. Addressing systemic barriers such as limited technical literacy and inadequate infrastructure, the ontology supports the use of cost-effective mobile applications for data entry and tracking. Pilot programs targeting smallholder farms could serve as test cases for these solutions, supported by government subsidies or international funding to promote widespread adoption.

Capacity building and education are essential to the success of the ATO's implementation. Training programs tailored to different stakeholder categories can bridge gaps in technical knowledge and ensure effective use of the ontology. These programs should emphasize hands-on experience with tools like Protégé for ontology visualization and data management, empowering users to fully utilize the system's capabilities.

The regulatory landscape will also need to adapt to support the ATO's implementation. Policies mandating the use of ontology-based traceability systems for cattle exports can help ensure compliance with international trade standards, such as those established by the World Trade Organization (1998), the European Union (2019), and the European Commission (2024). This alignment with global trade requirements can create a competitive advantage for Botswana's livestock sector, enhancing market access and economic sustainability.

The ATO represents a practical and scalable solution to the challenges faced by Botswana's animal husbandry sector. Its implementation can foster improved livestock management, enhance compliance with trade regulations, and support sustainable economic growth, demonstrating the real-world relevance and transformative potential of ontology-based knowledge management systems.

Research Limitations and Future Work

This study has several limitations. The development and testing of the ATO were primarily conducted within the context of Botswana's livestock industry, potentially limiting its applicability in other geographical or cultural settings without appropriate customization. Additionally, reliance on specific technological tools such as Protégé and Apache Jena Fuseki may hinder adoption in regions with restricted access to such resources. Furthermore, the ontology's current focus on cattle reduces its applicability to other livestock species, highlighting the need for expansion and adaptation to encompass a more diverse range of animals.

Future studies should focus on collecting and analyzing quantitative data before and after the implementation of the ATO to provide a clearer picture of the ontology's tangible benefits. Such an analysis could include metrics such as query performance, data accuracy, stakeholder satisfaction, and economic outcomes, offering a robust evaluation of the ontology's impact in practical scenarios. Future research should also extend the ATO to include additional livestock species, enhancing its adaptability to varied agricultural contexts and addressing the needs of different stakeholders. Incorporating real-time data processing capabilities would improve the ontology's responsiveness to urgent health and safety concerns while integrating advanced technologies such as blockchain and IoT could bolster data security, traceability, and transparency. Collaboration with international organizations and stakeholders could further support the standardization and global adoption of the ATO, fostering more robust and effective traceability systems. Additionally, leveraging Botswana's leadership in livestock traceability offers an opportunity to drive regional innovation, making the ATO a scalable and adaptable model for broader applications across Southern Africa and beyond.

References

Al-Adwan, A. S., & Sammour, G. (2021). What makes consumers purchase mobile apps: Evidence from Jordan. *Journal of Theoretical and Applied Electronic Commerce Research, 16*(3), 562-583. https://doi.org/10.3390/jtaer16030034

Alarcon, P., Fèvre, E. M., Murungi, M. K., Muinde, P., Akoko, J., Dominguez-Salas, P., Kiambi, S., Ahmed, S., Häsler, B., & Rushton, J. (2017). Mapping of beef, sheep and goat food systems in Nairobi – A framework for policy making and the identification of structural vulnerabilities and deficiencies. *Agricultural Systems*, *152*, 1-17. https://doi.org/10.1016/j.agsy.2016.12.005

Allouch, S., Amechnoue, K., & Achatbi, I. (2023). An ontological approach to model outbound logistics based on Internet of Things (OLP-IOT). *International Journal of Supply and Operations Management, 10*(4), 456-464. https://doi.org/10.22034/IJSOM.2023.109230.2270

Bahta, S., & Malope, P. (2014). Measurement of competitiveness in smallholder livestock systems and emerging policy advocacy: An application to Botswana. *Food Policy, 49*(2), 408–417. https://doi.org/10.1016/j.foodpol.2014.10.006

Bahta, S., Temoso, O., Ng'ombe, J. N., Rich, K. M., Baker, D., Kaitibie, S., & Malope, P. (2023). Productive efficiency of beef cattle production in Botswana: A latent class stochastic meta-frontier analysis. *Frontiers in Sustainable Food Systems, 7*, 1098642. http://doi.org/10.3389/fsufs.2023.1098642

Bai, H., Zhou, G., Hu, Y., Sun, A., Xu, X., Liu, X., & Lu, C. (2017). Traceability technologies for farm animals and their products in China. *Food Control, 79*, 35-43. https://doi.org/10.1016/j.foodcont.2017.02.040

Batlajery, B. V., Weal, M., Chapman, A., & Moreau, L. (2018, January-February). prFood: Ontology principles for provenance and risk in the food domain. *Proceedings of 12th IEEE International Conference on Semantic Computing, Laguna Hills, CA, USA,* 17-24. https://doi.org/10.1109/ICSC.2018.00012

Botswana Meat Commission. (2024). *Botswana beef.* https://bmc.bw/botswana-beef

Chatibura, D. M. (2023). Beef as intangible cultural heritage in Botswana: A documentary review. *Journal of Ethnic Foods*, 10, Article 41. https://doi.org/10.1186/s42779-023-00199-y

Creswell, J. W., & Creswell, J. D. (2022). *Research design: Qualitative, quantitative, and mixed methods approaches* (6th edition). Sage.

Creswell, J. W., & Guetterman, T. C. (2018). *Educational research: Planning, conducting, and evaluating quantitative and qualitative research* (6th ed.). Pearson.

Dizyee, K., Baker, D., & Rich, K. M. (2017). A quantitative value chain analysis of policy options for the beef sector in Botswana. *Agricultural Systems, 156*, 13–24. https://doi.org/10.1016/j.agsy.2017.05.007

Dooley, D., Griffiths, E., Gosal, G., Buttigieg, P. L., Hoehndorf, R., Lange, M., Schriml, L., Brinkman, F., & Hsiao, W. (2018). FoodOn: A harmonized food ontology to increase global food traceability, quality control and data integration. *npj Science of Food, 2*, Article 23. https://doi.org/10.1038/s41538-018-0032-6

European Commission. (2024). *Identification and registration of certain kept terrestrial animals*. https://food.ec.europa.eu/animals/identification_en

European Union. (2019). *Commission Delegated Regulation (EU) 2019/2035 of 28 June 2019*. https://eur-lex.europa.eu/eli/reg_del/2019/2035/oj

Fernandez, M., Gómez-Pérez, A., & Juristo, N. (1997, March). Methontology: From ontological art towards ontological engineering. *Proceedings of the AAAI Spring Symposium,* 33-40.

Food and Agriculture Organization of the United Nations. (2023). *The state of food and agriculture 2023 – Revealing the true cost of food to transform agrifood systems*. Rome. https://doi.org/10.4060/cc7724en

Frendi, M., Nachet, B., & Adla, A. (2024). Physical internet based ontology for supporting traceability in logistic I0T. *International Journal of Computing and Digital Systems, 15*(1), 427–440. https://iiict.uob.edu.bh/IJCDS/papers/IJCDS150133_1570894267.pdf

Fuentes, V., Martin, T., Valtchev, P., Diallo, A., Lacroix, R., & Leduc, M. (2022, May). DCPO: The dairy cattle performance ontology, a tool for domain modelling and data analytics. *Proceedings of the 45th ICAR Annual Conference, Montreal, Quebec, Canada,* 56-65. https://doi.org/10.1016/j.procs.2021.08.126

Gofamodimo, R. (2022, February 24). Botswana cattle population declines drastically. *Farmers' Review*. https://farmersreview.co.bw/2022/02/24/botswana-cattle-population-declines-drastically/

Government of Botswana. (2022). *Ministry of Agricultural Development and Food Security*. https://www.gov.bw/ministries/ministry-agriculture

Guest, G., Bunce, A., & Johnson, L. (2006). How many interviews are enough? An experiment with data saturation and variability. *Field Methods, 18*(1), 59–82. https://doi.org/10.1177/1525822X05279903

Hemnil, P., Boonchieng, E., & Osiriphun, S. (2023, January). Food safety block chain system using ontology in UHT milk factory. *Proceedings of the 17th International Conference on Ubiquitous Information Management and Communication, Seoul, Republic of Korea,* 1-5. https://doi.org/10.1109/IMCOM56909.2023.10035606

Hennink, M., & Kaiser, B. N. (2022). Sample sizes for saturation in qualitative research: A systematic review of empirical tests. *Social Science & Medicine, 292,* 114523. https://doi.org/10.1016/j.socscimed.2021.114523

Kampan, K., Tsusaka, T. W., & Anal, A. K. (2022). Adoption of blockchain technology for enhanced traceability of livestock-based products. *Sustainability, 14*(20), 13148. https://doi.org/10.3390/su142013148

Koncová, D., & Kremeňová, I. (2022). Interoperability and its significance. *Transport and Communications, 10*(1), 6-9. https://doi.org/10.26552/tac.c.2022.1.2

Lavoie, G., & Forest, J. F. (2009). Implementation of a traceability system from constraints to opportunities for the industry: A case study of Quebec, Canada. *International Food and Agribusiness Management Review*, *12*(2), 71-80. https://doi.org/10.22004/ag.econ.53753

Magliulo, L., Genovese, L., Peretti, V., & Murru, N. (2013). Application of ontologies to traceability in the dairy supply chain. *Agricultural Sciences, 4*(5), 41-45. https://doi.org/10.4236/as.2013.45b008

Mann, K. (2024, October 31). The largest agriculture sector in Botswana: Cattle and livestock. *ProAgri Media*. https://proagri.co.za/the-largest-agriculture-sector-in-botswana-cattle-and-livestock

Mauerman, M., Tjiseua, V., & Groves, D. W. (2023). Seeing cattle like a state: Sedentist assumptions of the Namibian Livestock Identification and Traceability System. *Nomadic Peoples*, 27(2), 171-197. https://doi.org/10.3197/np.2023.270202

Ministry of Agricultural Development and Food Security. (2018). *Botswana Animal Information and Traceability System (BAITS). Farmers guidelines scope*. Government of Botswana. https://www.gov.bw/sites/default/files/2020-03/(BAITS)%20Farmers%20Guidelines%20Scope.pdf

Mwanga, G., Mbega, E., Yonah, Z., & Chagunda, M. G. G. (2020). How information communication technology can enhance evidence-based decisions and farm-to-fork animal traceability for livestock farmers. *The Scientific World Journal, 2020*(1), Article 1279569. https://doi.org/10.1155/2020/1279569

Ouf, S. (2022). Ontology-based knowledge modelling for food supply chain data representation. *International Journal of e-Collaboration, 18*(1), 1-15. https://doi.org/10.4018/IJeC.299009

Pizzuti, T., Mirabelli, G., Grasso, G., & Paldino, G. (2016). MESCO (MEat Supply Chain Ontology): An ontology for supporting traceability in the meat supply chain. *Food Control*, *72*(A), 123-133. https://doi.org/10.1016/j.foodcont.2016.07.038

Pizzuti, T., Mirabelli, G., Sanz-Bobi, M. A., & Goméz-Gonzaléz, F. (2014). Food Track & Trace ontology for helping the food traceability control. *Journal of Food Engineering, 120*, 17-30. https://doi.org/10.1016/j.jfoodeng.2013.07.017

Prinsloo, T., & de Villiers, C. (2017). A framework to define the impact of sustainable ICT for agriculture projects: The Namibian Livestock Traceability System. *The Electronic Journal of Information Systems in Developing Countries, 82*(6), 1-22. https://doi.org/10.1002/j.1681-4835.2017.tb00606.x

Ramadhan, A., Arymurthy, A. M., Sensuse, D. I., & Muladno. (2021). Modeling e-Livestock Indonesia. *Heliyon, 7*(8), e07754. https://doi.org/10.1016/j.heliyon.2021.e07754

Resti, Y., Gutierrez Reynoso, G., Probst, L., Indriasari, S., Mindara, G. P., Hakim, A., & Wurzinger, M. (2024). A review of on-farm recording tools for smallholder dairy farming in developing countries. *Tropical Animal Health and Production, 56*, Article 168. https://doi.org/10.1007/s11250-024-04024-9

Saldana, J. (2021). *The coding manual for qualitative researchers* (4th ed.). Sage.

Statistics Botswana. (2020). *Annual agricultural survey report 2019 – Traditional sector*. https://www.statsbots.org.bw/sites/default/files/publications/ANNUAL%20AGRICULTURAL%20SURVEY%20REPORT%202019%20TRADITIONAL%20SECTOR.pdf

Storoy, J., Thakur, M., & Olsen, P. (2013). The TraceFood framework - Principles and guidelines for implementing traceability in food value chains. *Journal of Food Engineering, 115*(1), 41-48. https://doi.org/10.1016/j.jfoodeng.2012.09.018

Tartir, S., Arpinar, I. B., & Sheth, A. P. (2010). Ontological evaluation and validation. In R. Poli, M. Healy, & A. Kameas (Eds.). *Theory and applications of ontology: Computer applications* (pp. 115-130). Springer. https://doi.org/10.1007/978-90-481-8847-5_5

Temoso, O., Villano, R., & Hadley, D. (2016). Evaluating the productivity gap between commercial and traditional beef production systems in Botswana. *Agricultural Systems, 149*(11), 30-39. https://doi.org/10.1016/j.agsy.2016.07.014

Tongco, M. D. C. (2007). Purposive sampling as a tool for informant selection. *Ethnobotany Research and Applications, 5,* 147-158. https://doi.org/10.17348/era.5.0.147-158

Vallat, B. (2009). *Animal identification and product traceability from the farm to the fork must be progressively implemented worldwide*. World Organisation for Animal Health. https://www.woah.org/fileadmin/vademecum/eng/PDF_WORD_Vademecum/DELEGUE_FINAL/Slide%207/EN/Securite_sanitaire_des_aliments/04042008/Animal%20identification%20and%20product%20traceability.pdf

van Marle-Köster, E., Visser, C., Makgahlela, M., & Cloete, S. W. P. (2015). Genomic technologies for food security: A review of challenges and opportunities in Southern Africa. *Food Research International, 76,* 971–979. https://doi.org/10.1016/j.foodres.2015.05.057

World Organisation for Animal Health. (2011). *Botswana PVS gap analysis report: Strengthening veterinary services for international compliance.* https://www.woah.org/fileadmin/Home/eng/Support_to_OIE_Members/pdf/PVSGapAnalysis-Report-Botswana.pdf

World Organisation for Animal Health. (2024). *Terrestrial animal health code* (24th ed.). https://www.woah.org/en/what-we-do/standards/codes-and-manuals/terrestrial-code-online-access/

World Trade Organization. (1998). *WTO agreements series - sanitary and phytosanitary measures.* https://www.wto.org/english/res_e/booksp_e/agrmntseries4_sps_08_e.pdf

Zhao, J., Li, A., Jin, X., & Pan, L. (2020). Technologies in individual animal identification and meat products traceability. *Biotechnology and Biotechnological Equipment, 34*(1), 48-57. https://doi.org/10.1080/13102818.2019.1711185

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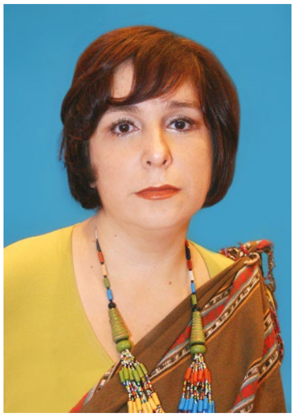

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