Designing a conceptual baseline digital traceability prototype and FMECA-based quality risk mapping for Indonesia's retail-oriented beef post-slaughter cold chain

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Abstract. Indonesia's beef supply chain continues to face quality assurance and traceability challenges, particularly in post-slaughter operations within retail-oriented cold chains. While upstream livestock identification systems are relatively well established, downstream processes such as carcass breakdown, secondary processing, distribution, and retail repackaging often result in identity fragmentation, temperature deviations, and incomplete documentation. This study integrates quality risk analysis with the design of a digital traceability system for post-slaughter beef handling. A bibliometric review of Scopus-indexed literature (2015–2025) yielded 593 eligible journal articles. Fieldwork involved supply chain mapping across one slaughterhouse, one distribution facility, and two retail outlets, supported by observations, document analysis, and expert input. FMECA was applied to prioritize failure modes based on severity, occurrence, and detectability. The findings indicate that key risks are predominantly structural, including identity fragmentation, temperature instability, and undocumented handling practices. A conceptual QR-based traceability prototype using parent–child batch genealogy was developed and evaluated through scenario-based workflow simulation. This study proposes a risk-based traceability framework to enhance batch continuity, governance transparency, and consumer trust in Indonesia's retail beef cold chain.

1 Introduction

Recent years have witnessed a substantial increase in global research attention toward food traceability, particularly within meat supply chains. Bibliometric analysis using VOSviewer on Scopus-indexed literature published between 2015 and 2025 reveals three dominant research streams (Figure 1). The first cluster centers on food safety, with a strong emphasis

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on microbial hazards, antibiotic resistance, and molecular detection technologies. The second cluster focuses on meat quality, including protein degradation, cold-chain management, muscle characteristics, and oxidative processes. The third cluster is dominated by blockchain and digital technologies, emphasizing data governance, cybersecurity, and supply chain transparency.

Overlay visualization (Figure 2) indicates a chronological shift in research focus, from laboratory-based food safety detection during 2020–2021, toward meat quality management in 2022–2023, and most recently to digital traceability frameworks in 2024–2025. Density mapping (Figure 3) further confirms that biological hazard control and blockchain-based systems are well established as independent research domains, while studies integrating digital traceability with operational quality control remain comparatively limited. Network analysis also demonstrates weak connectivity between digital system clusters and meat quality research. Collectively, these patterns reveal a critical global research gap: the absence of integrative frameworks linking digital traceability, quality management, and operational risk, particularly within retail-oriented meat systems.

Within Indonesia, food safety is recognized as a central pillar of national food security under Food Law No. 18/2012, which mandates not only food availability but also safety, nutritional value, quality, and affordability. In the beef sector, national carcass and meat standards are regulated under SNI 9226:2023, and slaughtering activities are required to be conducted at certified slaughterhouses holding a Veterinary Control Number (NKV). NKV certification ensures compliance with hygiene and sanitation requirements and forms the foundation of the ASUH principles (Safe, Healthy, Whole, and Halal). However, implementation remains uneven, and regulatory attention continues to concentrate primarily at the production level. Formal traceability beyond slaughter, particularly within retail operations, remains weakly regulated, resulting in limited visibility over handling practices, batch identity, and downstream cold-chain integrity.

A national-level study by Purnama (2021) established Indonesia's comprehensive digital traceability framework by integrating RFID, QR codes, and a centralized cattle database. Using a structured Software Development Life Cycle (SDLC) approach, the SICADAS.com prototype enabled information exchange across supply-chain actors and provided consumer-facing traceability through QR codes. Consumer modeling demonstrated that trust, product attributes, and traceability significantly influenced purchase intention, whereas perceived risk did not. These findings positioned traceability not merely as a data management tool but as a mechanism for building consumer trust [1].

Traceability has been formally defined as the ability to trace and follow a food product through all stages of production and distribution, enabling the reconstruction of its history and associated processes. Beyond regulatory compliance, effective traceability systems contribute to supply-chain optimization, product safety assurance, and enhanced market competitiveness by ensuring timely and consistent information flow across actors. In fragmented agri-food systems, traceability functions not merely as a tracking mechanism but as an information architecture that connects upstream and downstream nodes within a coherent governance framework [2].

Subsequent studies further indicate that food traceability is increasingly viewed not only as a regulatory instrument but also as a strategic component of agribusiness sustainability and competitiveness. Yusriana (2022) emphasized that product quality specifications and authenticity verification have become critical demands among food consumers. Through a comprehensive bibliometric review, the study classified traceability research into two major streams: conventional systems based on manual documentation and digital systems supported by information technology. Using clustering analysis, Yusriana demonstrated that digital traceability systems are emerging as the dominant research direction, driven by demands for real-time data, transparency, and system integration. The study also highlighted a shift from conceptual traceability models toward implementation-oriented frameworks, with practical applications in cacao and Arabica Gayo coffee supply chains [3].

Evidence from industry-level implementation studies further reinforces the operational value of traceability systems in quality assurance. Harahap (2020) reported that consumer rejection of food products is frequently associated with quality non-conformities and failure to meet national standards. In a case study of fish processing at PT Ardena Artha Mulia, traceability implementation through tracking and tracing mechanisms improved process control across production stages, from raw material intake to product dispatch. Production codes embedded in monitoring forms enabled rapid problem identification and root-cause analysis, confirming that traceability functions not merely as documentation but as an operational instrument for quality governance [4].

Parallel developments are also evident within the halal agri-food sector. Azmar (2024) identified that increasing awareness of halal authenticity and product integrity has intensified demand for advanced traceability systems. Using a qualitative literature-based approach, the study highlighted the potential of blockchain technology to combat food fraud, manage supplier accountability, and strengthen quality assurance across geographically dispersed production networks [5]. Beyond operational efficiency, blockchain-supported traceability was shown to contribute to the Sustainable Development Goals (SDGs), particularly Goal 9 (Industry, Innovation, and Infrastructure) and Goal 12 (Responsible Consumption and Production), by enhancing transparency, resilience, and trust within halal food markets.

Collectively, these studies demonstrate that traceability has evolved from a compliance-driven concept into a strategic mechanism for safeguarding quality, building consumer trust, and supporting market sustainability. However, existing research remains largely commodity-specific and often focuses either on technological infrastructure or consumer perception in isolation. Limited attention has been given to integrating traceability architecture with systematic quality risk mapping, particularly within post-slaughter beef supply chains and retail environments. This gap provides a strong justification for developing a quality-driven digital traceability framework supported by Failure Mode, Effects, and Criticality Analysis (FMECA).

Despite its foundational contribution, existing Indonesian traceability research has primarily addressed livestock identification, institutional readiness, information architecture, and consumer behavior. Post-slaughter operations where quality deterioration may arise from temperature deviations, sanitation failures, cross-contamination, portioning practices, and batch mixing have not been systematically examined. Moreover, prior frameworks have functioned predominantly as database platforms rather than as operational quality-control mechanisms embedded within daily cold-chain practices.

In practice, post-slaughter beef handling in Indonesia's retail sector is characterized by high operational variability. Beef portions are frequently rehandled during cutting, repacking, display, and short-term storage, often across multiple temperature zones within the same facility. Batch identity may be diluted through product mixing, manual labelling, or partial repackaging, while sanitation records and temperature logs are commonly maintained in fragmented, paper-based formats. These conditions create significant challenges for traceability continuity and quality accountability at the retail level, even when upstream slaughter operations comply with formal standards.

For locally sourced cattle processed in traditional slaughterhouses, post-slaughter handling is often conducted without systematic temperature measurement or standardized product labelling. Cold-chain control is typically implicit rather than recorded, and traceability relies largely on physical separation or verbal information. These practices constrain the ability to maintain batch integrity and to assess cumulative quality risks as products move toward retail distribution.

Even in certified export-oriented or modern slaughterhouses, traceability systems are generally confined to internal operations. Carcass or meat box labels commonly reflect processing dates, lot numbers, and responsible personnel within the slaughterhouse; however, individual meat portions become unidentifiable once removed from the original box. During distribution, boxes may be mixed, repacked, or partially allocated to different buyers, further diluting batch continuity. When whole cuts are transferred to processing units or modern retail markets, new retail labels are typically applied for display or packaging purposes, yet these labels are not systematically linked to the original slaughterhouse identifiers. This fragmentation creates a critical traceability gap at the post-slaughter interface, where quality risks related to sanitation, temperature abuse, and cross-contamination are most likely to accumulate but remain least visible.

From an information systems perspective, this research positions digital traceability as a structured information architecture that supports operational quality control rather than a stand-alone documentation tool. Recent studies indicate that digital traceability systems increasingly function as integrated information frameworks that enhance transparency, data continuity, and quality governance within food supply chains. Accordingly, this study emphasizes how quality risk identification can be translated into system-relevant data structures, information flows, and batch relationships applicable to post-slaughter beef handling and retail operations.

Consumer confidence in food systems is strongly influenced by transparency and labeling policies. Empirical evidence suggests that consumers value credible information regarding product origin and production processes, even when mandatory labeling schemes are not universally required. This underscores the importance of traceability systems that provide accessible and verifiable information at the point of purchase, particularly through consumer-facing interfaces such as QR codes [6].

To address this gap, Failure Mode, Effects, and Criticality Analysis (FMECA) was employed instead of conventional FMEA to enable structured risk prioritization based on severity and likelihood within routine retail operations, where cumulative minor deviations may compromise product quality. This study shifts Indonesia's digital traceability discourse from livestock registration toward retail-oriented quality governance. The objectives are to: (1) map the retail-focused post-slaughter beef supply chain; (2) identify and prioritize key quality and traceability risks using FMECA; and (3) develop a baseline digital traceability prototype capturing batch identity, sanitation compliance, temperature exposure, and product movement.

The prototype is designed as a conceptual baseline system emphasizing operational feasibility, hybrid manual digital data capture, and compatibility with existing quality assurance practices. It culminates in a consumer-facing QR code at the retail level, providing structured traceability information including cattle origin, slaughterhouse identification, post-slaughter handling stages, available temperature exposure records, and documented physical, chemical, or microbiological risk events. By integrating upstream and downstream data into a unified access point, the prototype functions as a practical framework for strengthening downstream beef quality governance and transparency in Indonesia, positioning traceability as an extension of routine retail-level quality risk management rather than a standalone information system.

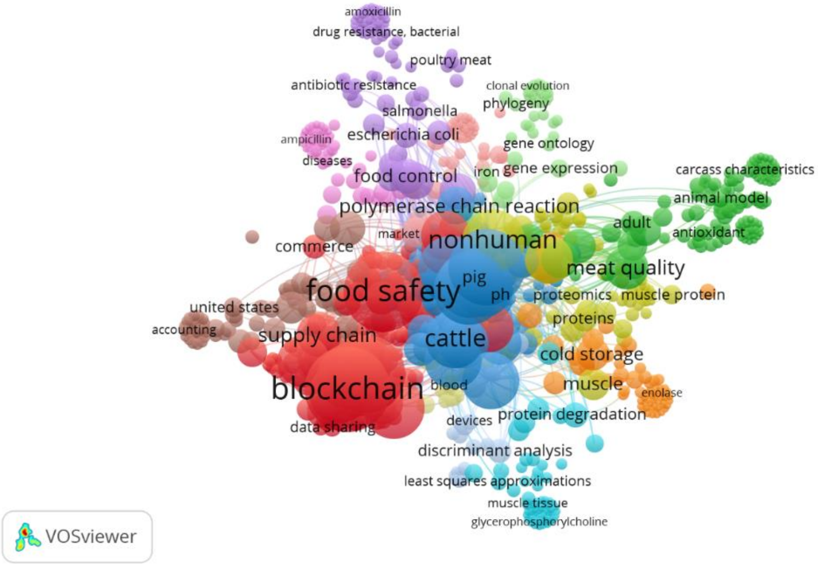

Fig. 1. Keyword co-occurrence network of beef traceability research (Scopus, 2015–2025) generated using VOSviewer.

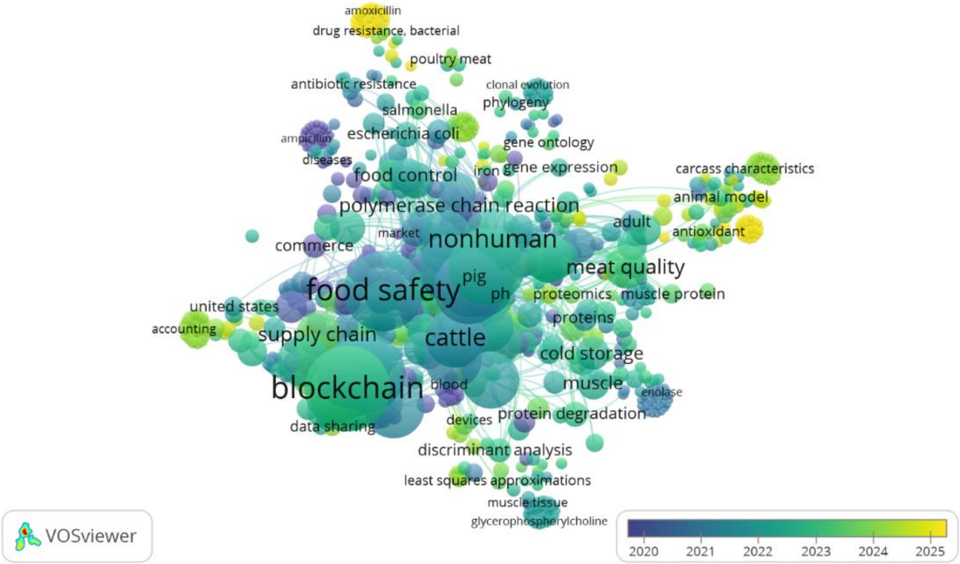

Fig. 2. Overlay visualization of keyword evolution in beef digital traceability research (Scopus, 2015–2025) using VOSviewer.

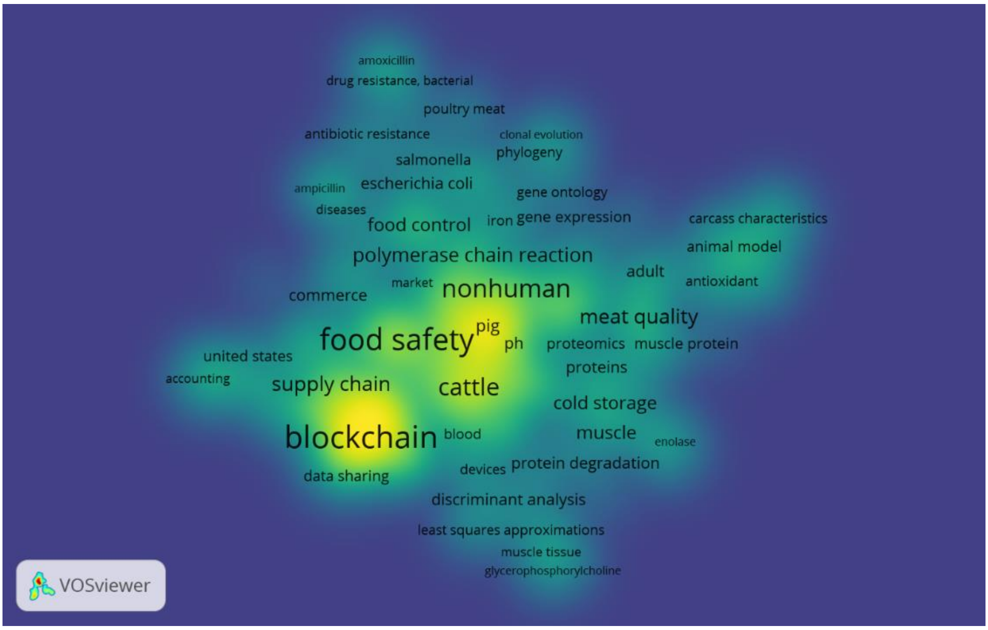

Fig. 3. Density visualization of research intensity in beef digital traceability (Scopus, 2015–2025) generated using VOSviewer.

2 Methodology

2.1 Bibliometric analysis and conceptual framing

This study commenced with a structured bibliometric review of peer-reviewed journal articles indexed in the Scopus database published between 2015 and 2025. The search string applied was: ("beef" OR "meat") AND ("digital traceability" OR "traceability system") AND ("food quality" OR "food system" OR "supply chain"). Inclusion criteria comprised peer-reviewed journal articles published in English within the specified time frame. Exclusion criteria included conference proceedings, book chapters, non-English publications, and studies unrelated to meat commodities. Following screening and eligibility assessment, 593 documents were retained for analysis. Bibliometric mapping and visualization were conducted using VOSviewer to identify dominant research clusters, temporal publication trends, and co-occurrence networks among key themes. The findings informed the analytical direction of the study, supported the identification of research gaps, and contributed to the development of the conceptual framework linking digital traceability, quality governance, and operational risk management.

2.2 Supply chain mapping and field data collection

Following the bibliometric review, a baseline exploratory approach was adopted to examine Indonesia's retail-oriented post-slaughter beef cold chain. Field data were collected through site observations at selected post-slaughter and retail-related facilities, informal interviews with operational personnel involved in meat handling and quality control, and reviews of routine quality-control documents. Facilities were selected purposively to represent key downstream nodes within Indonesia's retail-oriented beef cold chain, including one certified slaughterhouse, one distribution facility handling both domestic and imported beef, and two retail outlets representing modern and small-scale retail operations. Selection was based on operational relevance, willingness to provide access, and representativeness of common post-slaughter handling practices. These documents included temperature monitoring records, sanitation and hygiene checklists, and shipment or distribution logs where available. Observed handling practices were systematically translated into process flow diagrams to visualize physical product movement, information flows, and key operational interfaces influencing meat quality. Attention was given to points where batch identity, temperature control, sanitation practices, and documentation continuity were most likely to be compromised.

2.3 Quality risk identification using FMECA

Failure Mode, Effects, and Criticality Analysis (FMECA) was applied as a qualitative risk assessment tool to identify and prioritize dominant quality and traceability risks within the post-slaughter retail chain. FMECA was selected over conventional FMEA to enable prioritization of risks based on both severity and likelihood within routine retail operations, where multiple minor deviations may cumulatively affect product quality.

Potential failure modes were identified across critical handling stages, including temperature deviations, sanitation lapses, batch mixing, and documentation errors. Each failure mode was evaluated using three parameters: severity, occurrence, and detection. Scoring was conducted using a simplified five-point scale, based on expert judgment, field observations, and consistency with routine quality assurance practices. Criticality rankings were subsequently used to determine priority risk areas requiring traceability intervention.

Failure Mode and Effects Analysis (FMEA), and its extension FMECA, are widely applied tools for identifying potential failures and prioritizing risk mitigation actions. However, the traditional Risk Priority Number (RPN) approach has been criticized for methodological limitations, prompting the development of enhanced evaluation models and structured scoring approaches. Despite these limitations, structured expert-based FMECA remains an effective method for operational risk prioritization in contexts where historical failure data are limited [7].

2.4 Digital traceability prototype design

Results from the FMECA served as the primary input for designing a baseline digital traceability prototype. The prototype was intentionally developed as a low-barrier, manual–digital hybrid system, focusing on operational feasibility and compatibility with existing quality assurance practices. Key data elements incorporated into the prototype included batch identity, post-slaughter handling stages, sanitation verification, temperature exposure records where available, and documented quality or safety-related events associated with physical, chemical, or microbiological hazards. The prototype represents a conceptual baseline design and was verified through scenario-based workflow simulation and expert walkthrough, rather than full operational piloting.

The system culminates in a consumer-facing QR code applied at the retail level, allowing access to structured traceability information relevant to purchasing decisions. The QR code functions as an interface linking upstream and downstream data without requiring advanced automation or infrastructure.

The prototype design process applies core principles of information system analysis, including identification of critical data entities, definition of batch hierarchy, and mapping of information flows across post-slaughter handling stages. This approach ensures that the proposed traceability system structure directly reflects operational risks identified through

FMECA, consistent with previous applications of FMECA as a foundation for traceability system design in food industries.

2.5 Research positioning

This methodological approach represents a baseline phase within a longer-term research agenda aimed at developing an integrated, quality-driven digital traceability framework for Indonesia's beef retail system. Rather than validating technological performance, the present study emphasizes system structure, risk relevance, and practical applicability within real operational constraints.

3 Results and discussion

3.1 Beef supply chain mapping

At the national level, Indonesia's beef demand cannot yet be fully met by domestic production, resulting in continued reliance on imports of feeder cattle and frozen beef. This structural supply deficit is compounded by persistent domestic challenges, including low on-farm productivity, limited human resources and infrastructure, and long, fragmented distribution chains between producers and final consumers. Across these chains, most actors continue to operate without systematic record-keeping, which substantially constrains the availability of reliable data for effective traceability and quality monitoring.

Food traceability has increasingly been conceptualized as an integral component of logistics management rather than a standalone information tool. Integrating traceability within logistics processes ensures continuity of information flow, improves recall efficiency, and enhances crisis management performance. This perspective reinforces the need to embed batch-level data inheritance and transformation tracking within operational workflows, particularly in complex, multi-node supply chains such as post-slaughter beef distribution [8].

From a logistical perspective, Indonesia's beef supply chain can be broadly differentiated into intra-island and inter-island flows. Intra-island chains, particularly within Java, typically involve cattle raised in production centers such as East Java (e.g., Tuban and Bojonegoro), transported to urban slaughterhouses, and subsequently distributed to traditional and modern markets in Jakarta and surrounding regions. Inter-island chains predominantly move cattle from major producing regions outside Java, including Nusa Tenggara Timur (NTT), Nusa Tenggara Barat (NTB), and Bali, to consumption centers in Java, Kalimantan, Sulawesi, and Sumatra. These movements rely on combined road transportation and dedicated live-cattle vessels, followed by redistribution through local traders and slaughterhouses.

Despite this structural complexity, formal traceability across the beef supply chain remains limited, particularly beyond the slaughter stage. For locally sourced cattle processed in traditional slaughterhouses, post-slaughter operations are frequently conducted without systematic temperature measurement, standardized product labelling, or formal batch identification. Cold-chain control is often implicit rather than recorded, and traceability relies largely on physical separation or verbal information. Once cattle are slaughtered and converted into carcasses, animal identification tags are rarely maintained, and beef often enters distribution channels without documented thermal history or batch identity before being sold directly in traditional markets.

More structured traceability practices are observed for imported feeder cattle operating under ESCAS-like schemes, where importers, feedlots, and slaughterhouses are required to maintain detailed records and deploy designated Animal Welfare Officers (AWOs) to monitor animal handling from port unloading through finishing and slaughter. However, even within these regulated systems, traceability remains largely confined to internal operations at the feedlot and slaughterhouse levels and is not systematically transferred downstream.

In parallel with live-cattle flows, Indonesia also imports frozen beef and beef cuts from countries such as Australia and Brazil. These products typically enter the supply chain at the off-farm stage and are received by large distributors or processing units as frozen blocks or primal cuts. At this stage, meat may undergo further processing into minced beef, sliced products, or smaller retail-ready portions, followed by repacking and labelling. Products are then distributed either to small retailers selling directly to consumers or to modern retail outlets for chilled display.

Within modern retail environments, two distribution modes commonly coexist. First, industrially packed products from processing units are sold as branded, pre-packed items. Second, in-store processing counters open bulk cartons or larger cuts, re-portion, re-pack, and label meat according to consumer demand. These additional transformation steps introduce new labelling layers and generate new sub-batches that are not systematically linked to the original slaughterhouse or import batch identifiers. As a result, batch integrity is progressively diluted as products move downstream.

The mapped post-slaughter beef supply chain thus exhibits a multi-path configuration rather than a single linear distribution flow, consistent with national beef value chain descriptions [1], as illustrated in Figure 4. Following slaughter, ante- and post-mortem inspection, and initial chilling at the slaughterhouse, carcasses typically undergo primary cutting, portioning, labelling, and cold storage before entering downstream distribution. Subsequent secondary processing, repackaging, and relabelling further fragment product identity and obscure traceability continuity.

Table 1 provides a detailed overview of the key activities, outputs, and documentation practices of major actors along Indonesia’s beef supply chain, adapted from Purnama (2021) with downstream extensions based on field observations. The table reveals a clear gradient in documentation structure across the chain. Upstream actors such as commercial feedlots, inter-island traders, and certified slaughterhouses generally maintain basic records related to animal numbers, live weights, carcass weights, inspection outcomes, and shipment documents. However, these records are primarily designed for transactional, regulatory, or logistical purposes and are rarely structured to support continuity of traceability beyond the immediate operational node.

As products move downstream, particularly at the wholesaler, processing, and retail levels, documentation practices become increasingly fragmented and facility-oriented rather than product- or batch-specific. Although batch or lot identifiers may be applied at slaughterhouse or processing-unit levels, these identifiers are frequently lost once products are removed from original cartons, re-portioned, minced, or repacked. Small retailers and traditional butchers operate with minimal formal documentation after further cutting or thawing, relying largely on daily sales notes and informal purchasing records without systematic linkage to origin, batch history, or temperature exposure.

Even within modern retail environments, where temperature monitoring and labelling practices are more structured, traceability continuity remains limited. Retail labels typically prioritize commercial information such as cut type, net weight, packing date, and expiry date, while backward linkage to slaughterhouse batches or animal identity is not maintained once in-store re-portioning and relabelling occur. Consequently, Table 1 demonstrates that traceability discontinuity is not caused by a complete absence of records, but rather by the lack of integration and transfer of identity and quality-related information across successive actors and transformation stages.

Across both traditional and modern retail channels, documentation and temperature monitoring are generally conducted at the facility level rather than as part of a continuous, product- or batch-specific data chain. Cold transportation and intermediate storage occur between each processing and delivery stage, further increasing exposure to temperature deviations and handling variability. Retail outlets ultimately function as aggregation points where products from multiple upstream sources converge, yet the cumulative handling history, cold-chain exposure, and sanitation context of individual retail cuts are rarely visible at the point of sale.

This structural configuration explains why downstream traceability failures persist despite relatively strong upstream governance mechanisms. Fragmentation of identity after slaughter, combined with multiple transformation steps and relabelling practices, weakens the ability to associate retail beef products with their original animal sources or specific processing conditions. Quality risks related to sanitation, temperature abuse, and cross-contamination are most likely to accumulate at these downstream stages yet remain the least visible to both regulators and consumers.

These findings reinforce the need for a traceability architecture that extends beyond simple registration of product movement and explicitly integrates quality and risk parameters at each post-slaughter transformation node. Without digital continuity across cutting, processing, storage, and retail operations, traceability remains administrative rather than functional as a quality control mechanism. This empirical mapping therefore provides a robust foundation for integrating FMECA-based risk prioritization into the design of a retail-oriented digital traceability prototype capable of preserving batch identity, supporting quality governance, and enhancing transparency at the consumer interface.

Traceability has gained prominence as a safety and quality assurance instrument, particularly following major food safety crises that exposed weaknesses in monitoring and recall systems. Well-designed traceability systems help minimize the distribution of unsafe products, reduce liability exposure, and restore consumer confidence by ensuring rapid identification of contamination sources. Accordingly, traceability should be interpreted as a governance mechanism linking risk control, quality monitoring, and accountability across the supply chain [9].

Table 1. Key activities, outputs, and documentation of beef supply chain actors in Indonesia adapted from Purnama (2021) with downstream extensions and modifications based on field observations.

Supply chain actor	Main activities	Typical outputs	Main records / documents
Smallholder farmers	Rear and grow cattle (calves, grower, fattening); provide forage and basic health care	Weaned calves, feeder cattle, or slaughter-ready cattle	Basic husbandry history (often informal); occasional notes on age, breed, and selling weight (usually estimated rather than weighed)
Local collectors	Purchase cattle from farmers or livestock markets; hold cattle short term (1–14 days); provide feed and basic health checks	Feeder or slaughter cattle aggregated from multiple farms	Purchase and sale lists; estimated live weights; simple movement records (if required by local authorities)
Inter-island traders	Aggregate cattle for inter-island shipment; arrange permits and quotas; hold cattle short term before shipping; manage loading, quarantine, and dispatch	Feeder or slaughter cattle shipped between islands	Transport permits and shipping licenses; quarantine documents; basic records of number of animals, estimated or weighed live weights at loading and arrival

Table 1. Key activities, outputs, and documentation of beef supply chain actors in Indonesia adapted from Purnama (2021) with downstream extensions and modifications based on field observations (continue).

Supply chain actor	**Main activities**	**Typical outputs**	**Main records / documents**
Sea transporters (live-cattle vessels)	Transport cattle from origin to destination ports; allocate animals to pens; provide feed, water, and veterinary supervision during voyage	Live cattle arriving at destination in acceptable condition	Manifests listing number of animals and weights; voyage records; basic health status reports
Road transporters (trucks)	Move cattle from farms to markets or quarantine, from ports to buyers, and from traders to slaughterhouses; transport carcasses or boxed meat from slaughterhouses to distributors and retailers	Live cattle or carcasses delivered to next node	Delivery notes and transport documents; occasional temperature records for refrigerated vehicles (where used)
Jakarta traders / feedlot operators	Purchase cattle from inter-island traders; hold and fatten cattle; sell to *bandar* or butchers	Fattened cattle ready for slaughter	Records of number of cattle, purchase and sale weights; basic feeding and health records (more structured in commercial feedlots)
Slaughterhouses (RPH) and bandar	Receive cattle from traders or feedlots; rest, feed, and inspect animals; stun, slaughter, dress, chill, and debone carcasses; produce commercial cuts; lease or operate slaughter facilities	Carcasses and commercial meat cuts supplied to wholesalers, butchers, Horeca, or processors	Live weight and carcass weight records; basic meat inspection and health certificates; sometimes breakdown weights by primal cut; limited linkage to downstream batch codes
Wholesalers / large meat distributors & processing units	Purchase carcasses, large cuts, or imported frozen beef (e.g., from Australia, Brazil); debone, trim, mince, slice, and portion meat; repack and label products; store in chillers/freezers; distribute to small retailers, modern retail, Horeca, and processors	Carcasses and primals; boxed meat; vacuum-packed or tray-packed chilled/frozen cuts; minced beef; sliced beef; small family-size portions	Inbound and outbound weight records; product specifications (cut type, fat content, origin where available); basic batch or lot codes (often internal); production dates and best-before dates; shipping documents (date, destination, vehicle); occasional storage temperature logs in larger facilities
Small retailers / traditional butchers	Purchase carcasses, sides, large cuts, or processed frozen packs from distributors; thaw (if frozen), cut into smaller commercial portions, and sell directly to households, small food outlets, and informal Horeca; store limited volumes in simple chillers or freezers	Fresh or thawed retail cuts (whole muscle, small portions, minced beef prepared on-site)	Basic purchase notes; daily sales and weight records; simple price and product notes; rare use of formal batch codes; very limited or no systematic temperature or origin documentation, especially after further cutting or mincing

Table 1. Key activities, outputs, and documentation of beef supply chain actors in Indonesia adapted from Purnama (2021) with downstream extensions and modifications based on field observations (continue).

Supply chain actor	Main activities	Typical outputs	Main records / documents
Modern retailers (supermarkets and hypermarkets)	Purchase boxed or portioned meat from importers, processors, and domestic distributors; receive both domestically produced and imported frozen/chilled beef; conduct in-store portioning and mincing at service counters; repack and label with store-specific SKUs; display in chilled cabinets or freezers; sell to households and Horeca clients	Pre-packed branded products from processing units; store-branded packed chilled/frozen beef; counter-cut fresh-looking meat packed to customer-requested weight; minced, sliced, and small family packs	Product receipts and invoices, often with origin/country-of-origin information; internal SKUs and lot codes; labelling with cut type, net weight, packing and expiry dates; chiller/freezer temperature logs (more systematic than traditional markets); however, backward linkage to original slaughter batch or animal identity is generally not maintained once products are re-portioned and relabelled in-store
End consumers (households, Horeca, food processors)	Purchase beef from small retailers or modern retailers; store, prepare, and consume products; in some cases, reprocess into cooked dishes or processed foods (e.g., meatballs, catering products)	Beef as consumed: raw, cooked, or processed products	Receipts or invoices; consumer labels (product name, date, retailer); typically, no access to slaughter or batch data

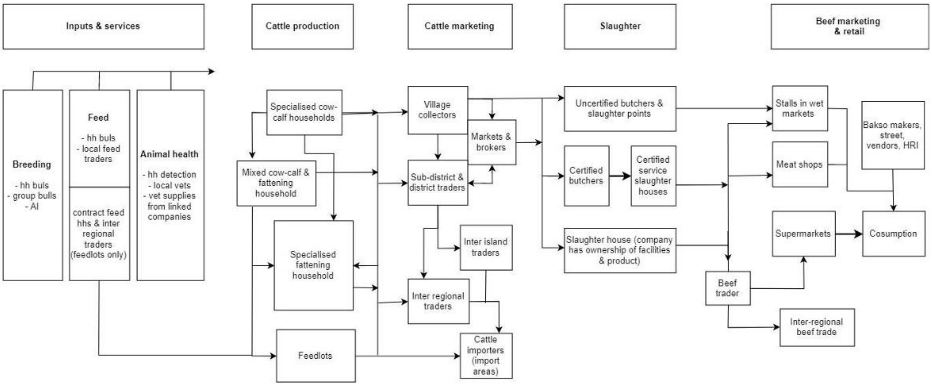

Fig. 4. Product flow within Indonesia's beef value chain

3.2 Failure Mode, Effects, and Criticality Analysis (FMECA)

Failure Mode, Effects, and Criticality Analysis (FMECA) is widely applied in the manufacturing sector as a structured risk assessment method to ensure machine availability, product reliability, and consistent quality delivery, thereby supporting customer satisfaction and corporate reputation. Beyond industrial applications, FMECA has gained increasing relevance in the food sector, where it is used to evaluate quality and safety risks across complex supply chains. In both contexts, FMECA functions not merely as a diagnostic tool but as a decision-support mechanism that guides risk mitigation by identifying the most vulnerable control points within operational systems [10].

For each identified failure mode, improvement actions are generally designed to reduce criticality through three dimensions: severity, occurrence, and detection. Corrective actions targeting root causes primarily reduce failure frequency, while improvements in monitoring and control mechanisms enhance detectability. Severity, however, is typically more difficult to mitigate and often requires substantial interventions such as process redesign, infrastructure upgrades, or system-level changes. Effective control strategies are therefore expected to improve at least one risk parameter, for example by lowering detection scores through the introduction of multiple verification or monitoring mechanisms.

In this study, FMECA was operationalized following classical procedural stages, including system definition, functional analysis, failure mode identification, risk scoring, and criticality determination. System definition focused on post-slaughter operations within Indonesia’s beef supply chain, encompassing slaughtering, chilling, carcass handling, cutting, processing, cold storage, transportation, secondary processing, retail operations, and consumer access. Functional analysis mapped operational relationships among actors, highlighting dependencies and interfaces affecting both product condition and information continuity.

Failure modes were identified at each control point, and their effects were evaluated at both local and system-wide levels. Severity (S) represented the magnitude of impact on product quality and traceability integrity, occurrence (O) reflected the frequency of failure under routine operations, and detection (D) indicated the capability of existing systems to identify failures before they affected product safety. Risk Priority Numbers (RPNs), calculated as the product of S, O, and D, provided a quantitative basis for prioritizing risk intervention.

The study acknowledges that precise quantification of severity, occurrence, and detection is inherently subjective, particularly in supply-chain environments where historical failure data are limited. Previous studies have emphasized that FMECA in food systems frequently relies on expert judgment and qualitative assessment approaches to enhance scoring reliability [11]. Accordingly, this research applied a structured expert panel discussion involving five domain experts, where scoring was conducted through facilitated consensus-building sessions. Initial individual ratings were discussed collectively, and final scores were determined through agreement-based deliberation to ensure contextual relevance and scoring consistency. Field observations were used to triangulate and validate expert assessments.

FMECA was applied across downstream operations from slaughtering to retail display to identify failure modes that simultaneously affect traceability continuity and product quality. Severity (S), occurrence (O), and detection (D) were evaluated using a structured five-point scale (1 = negligible and 5 = critical), with explicit operational definitions provided in Table X. Severity reflected the potential impact on food safety, product integrity, and consumer trust; occurrence represented the estimated frequency of failure under routine operational conditions; and detection indicated the likelihood of identifying the failure before product release. Risk Priority Number (RPN) values were calculated as the product of S, O, and D ($RPN = S \times O \times D$), yielding a possible range of 1 to 125. Based on proportional stratification of this maximum range and established risk-ranking logic in food-system FMEA/FMECA applications, RPN values were categorized into four levels to guide mitigation prioritization. RPN values of 80 or higher were classified as unacceptable and requiring immediate corrective action, values between 50 and 79 were considered undesirable and requiring mitigation, values between 20 and 49 were deemed acceptable with control and subject to monitoring, and values below 20 were categorized as low risk under routine control. The resulting FMECA-based risk mapping is summarized in Table 2.

The translation of FMECA results into traceability system requirements highlights the role of information system design in bridging risk analysis and operational implementation. Previous studies have demonstrated that traceability failures are often caused by information discontinuity rather than the absence of technology, underscoring the importance of system architecture that preserves data continuity and supports quality risk governance.

Empirical findings from the FMECA reveal that the most critical risks are not limited to biological contamination but are concentrated in structural failures related to identity loss and information discontinuity. At the slaughterhouse level, animal identity is initially available; however, routine operational practices commonly reorganize carcasses based on slaughter date rather than individual animal identifiers. As a result, production-day batching becomes the dominant classification mechanism, triggering early dilution of traceability unless digital identifiers are actively preserved.

This erosion of identity intensifies during carcass breakdown. Once carcasses are divided into quarters and commercial cuts, product identification shifts away from animal origin and becomes associated primarily with processing dates or internal batch codes. At this stage, traceability transitions from origin-based identification to process-based labelling. Operationally, the system no longer answers the question of which animal a product originated from, but only records when it was processed.

Further identity degradation occurs during distribution. Products shipped directly to retail outlets are commonly relabelled based on dispatch or receipt dates, introducing an additional layer of traceability discontinuity between slaughterhouse records and retail documentation. In alternative pathways, particularly those involving agents and secondary processors, beef is reprocessed into minced products, sliced cuts, or consumer-sized portions. These activities generate new batch identifiers that typically exclude upstream information such as slaughter identity, chilling history, sanitation verification, or responsible personnel. Moreover, secondary processing environments frequently operate outside standardized food safety frameworks such as NKV, HACCP, or BRCGS, resulting in inconsistent documentation and variable quality oversight.

At the retail level, repackaging for display further obscures quality history. Consumer-facing labels generally disclose packaging date, product name, and outlet information but omit critical parameters such as handling duration, cumulative temperature exposure, and sanitation status. Consequently, quality attributes related to freshness, microbial risk, and moisture loss remain operationally invisible. Identity and quality data cease to function as control instruments and are reduced to transactional descriptors.

Collectively, these conditions confirm that existing traceability practices within Indonesia's beef supply chain remain documentation-centric rather than quality-centric. Information is recorded but not preserved, performance is monitored but not analyzed, and identity is stored but not cascaded. Traceability therefore functions primarily as a reporting mechanism instead of an operational quality management system. These findings are consistent with previous studies demonstrating that effective traceability in tuna processing requires real-time acquisition of multiple control variables, including temperature, sanitation, and process flow. Their RFID-, GPS-, and CCTV-supported architecture illustrated how traceability can function as a continuous monitoring infrastructure rather than a passive data repository [12]. Traceability effectiveness depends not only on technology adoption but on integration within business process design. Using an SDLC-based architecture for the coconut agroindustry, they demonstrated that traceability must be embedded within comprehensive CBIS dimensions, encompassing hardware, software, dataware, netware, infoware, and brainware.

In this implementation context, dataware refers to the structured storage and management of raw traceability data, such as batch codes, temperature logs, sanitation checklists, and handling records captured across supply-chain nodes. In contrast, infoware denotes the transformation of these structured datasets into interpretable and decision-oriented outputs, including risk alerts, compliance summaries, batch genealogy visualization, and consumer-facing QR-based information displays. Thus, while dataware ensures data integrity and retrievability, infoware enables contextual interpretation and governance-oriented decision support.

Consumer-focused research further reinforces the strategic relevance of traceability. Safety, quality, animal welfare, and environmental sustainability attributes are associated with premium pricing [13]. Consumers in Canada were willing to pay more for beef traceable from farm to retail, particularly following disease outbreaks such as BSE. Country-of-origin labelling functions as a critical credence attribute in the aftermath of food safety crises.

Overall, the FMECA applied in this study demonstrates that traceability breakdowns in Indonesia's beef system are structural rather than technological. Dominant failures occur not because digital tools are unavailable, but because traceability is decoupled from quality management. Identity does not follow product flow, temperature exposure is not historically preserved, sanitation is performed but not digitally verified, and recall capability exists conceptually but collapses operationally. By embedding FMECA into traceability design, this study reframes digital traceability from an information system into a risk governance instrument. Interventions targeting occurrence reduction and detection improvement are prioritized, while severity mitigation requires infrastructure investment, redundancy systems, and mandatory digital identification at repackaging points [10]. These findings directly inform the design of the proposed digital prototype, which integrates batch identity, temperature records, sanitation logs, and product movement into a unified, quality-oriented traceability framework.

Given the five-point scoring scale for severity, occurrence, and detection (range 1–5), the maximum possible Risk Priority Number (RPN) was 125. To ensure proportional and interpretable risk stratification, RPN values were categorized into four levels based on relative position within the theoretical maximum score and practical risk-management considerations in food supply chains. Scores of 80 and above (≥64% of the maximum value) were classified as Unacceptable, indicating high combined severity, likelihood, and limited detectability, thus requiring immediate corrective intervention. RPN values between 40 and 79 were categorized as Undesirable, reflecting significant operational vulnerability requiring structured mitigation. Scores between 20 and 39 were considered Acceptable with Revision, indicating manageable risks subject to monitoring and incremental improvement. RPN values below 20 were classified as Low Risk, representing routine operational deviations under standard control. This proportional stratification approach aligns with commonly applied FMEA/FMECA risk-ranking practices in food safety management, where threshold determination balances mathematical distribution and practical governance priorities.

Table 2. FMECA-based risk mapping for Indonesia's retail-oriented post-slaughter beef cold chain.

ID	**Process stage**	**Failure mode**	**Potential cause**	**Local effect**	**Global effect**	**S**	**O**	**D**	**RPN**	**Risk level**	**Recommended action**
1	Slaughter & carcass ID	Loss of animal identity	No linkage between live-animal ID and carcass	Origin unclear at carcass level	Traceability break	5	4	5	100	**Unacceptable**	Enforce carcass-level ID (QR/RFID); auto-link live-animal ID

2	Chilling	No temperature log	Manual checks without records	Quality deviation not detected	Shelf-life reduced	4	4	4	64	**Unacceptable**	Install data logger; automatic upload
3	Deboning / cutting	Batch mixing	No zoning and batch segregation	Supplier unclear	Traceability irreversible	5	3	4	60	**Unacceptable**	SOP batch isolation; color-coded crates
4	Processing (agent / backroom)	No sanitation record	No verification system	Hygiene uncertain	Food safety risk	4	4	4	64	**Unacceptable**	Digital sanitation checklist
5	Packaging	Label mismatch	Manual data entry	Product misidentified	Recall complexity	4	3	3	45	**Undesirable**	Auto-generated batch labels
6	Cold storage	Temperature fluctuation	Door openings, weak alarms	Spoilage risk	Product degeneration	4	3	3	36	Acceptable w/ Revision	Alarm + audit log
7	Transport	No cold-chain record	Non-data trucks	Quality uncertain	Liability exposure	4	3	3	36	Acceptable w/ Revision	Portable loggers
8	Agent processing	Repacking without record	Informal processing	Origin erased	Legal non-compliance	5	3	4	60	**Unacceptable**	Mandatory batch ID at agent
9	Wholesale / distributor	Cross-dock without ID carry-over	Re-aggregation from multiple sources	Lot confusion	Recall scope	4	3	3	36	Acceptable w/ Revision	Enforce inbound–outbound ID mapping
10	Retail packaging (modern/small)	New batch ID	Store relabelling	Identity lost	No backward trace	5	3	4	60	**Unacceptable**	Preserve original ID on retail label
11	Retail display	No display log	Open cabinets, no monitoring	Unknown holding temp	Consumer risk	4	3	3	36	Acceptable w/ Revision	Digital display logs
12	Consumer interface	No access to data	No QR / portal	Transparency lost	Trust erosion	3	3	3	27	Acceptable w/ Revision	Consumer-facing QR
13	Documentation	Manual record	Paper-based	Delay	Recall slow	4	3	3	36	Acceptable w/ Revision	Central digital platform
14	Recall	Traceback failure	ID discontinuity	Root unknown	Market exposure	5	2	4	40	**Undesirable**	End-to-end trace
15	Temperature abuse	No alerting	Weak monitoring	Spoilage	Complaints	4	4	4	80	**Unacceptable**	Threshold alerts and automated notifications

3.3 Digital traceability prototype design

Based on the mapped supply chain structure and FMECA-based risk prioritization, a baseline digital traceability prototype was developed to restore batch-level continuity and capture critical quality-related information across Indonesia's post-slaughter beef cold chain. From a system design perspective, the prototype is conceptualized as a batch-oriented information architecture that prioritizes data continuity, inheritance, and scalability across successive transformation stages. Rather than proposing a fully automated or infrastructure-intensive solution, the model translates high-priority risks identity loss, temperature instability, and undocumented handling into structured data requirements and defined information flows. The prototype remains conceptual and was evaluated through scenario-based workflow simulation and expert walkthrough, without live operational deployment.

The core design principle is parent–child batch tracking. Each carcass is registered as a parent batch, and every subsequent physical transformation such as quartering, cutting, grinding, slicing, or repacking generates a new child batch that retains an explicit digital linkage to its parent. As illustrated in Figure 7, this structure follows a hierarchical one-to-many inheritance logic: a single parent carcass ID may generate multiple child batch IDs at each stage, while each child preserves backward traceability to both its immediate and original source. This unified batch genealogy enables continuous backward (consumer-to-origin) and forward (origin-to-distribution) traceability, preventing identity fragmentation even when products move across multiple facilities and undergo repeated repackaging.

Aligned with hierarchical data modelling principles commonly applied in information systems, this approach preserves data lineage across transformation processes and mitigates traceability loss frequently observed in fragmented food supply chains. To enhance feasibility within the current Indonesian context, the prototype is designed as a lightweight, form-based digital system that can be implemented initially using a spreadsheet-backed database or a simple web interface. The model emphasizes preservation of a minimum yet consistent dataset inherited across parent and child batches to maintain continuity throughout successive transformations.

The five core data categories are summarized in Table 3, which outlines the essential elements required to support batch continuity and risk-informed traceability. The prototype remains conceptual and was evaluated through scenario-based workflow simulation and structured expert walkthrough rather than live operational deployment. Accordingly, Table 3 represents a baseline data architecture intended to guide practical and scalable implementation. Information flows in the proposed system are designed to follow the physical product throughout post-slaughter handling. Each time a transformation occurs such as carcass cutting, portioning, grinding, or repacking a new digital record is generated. This record inherits the parent batch identifier and appends new information related to processing activities, temperature exposure, sanitation verification, responsible operators, and time–location stamps. In this way, batch identity and quality-relevant data are preserved cumulatively rather than overwritten or replaced.

At the retail level, the system assigns a single consumer-facing QR code to each retail pack. This QR code is linked to the internal traceability database and enables authorized users and, in later implementation stages, consumers to access a concise summary of product origin, post-slaughter handling history, and basic cold-chain compliance information. The QR code thus functions as an interface that reconnects upstream identity and quality data with downstream retail products without exposing sensitive operational details.

Slaughterhouses (RPH/RPU) serve as the initial data capture points, recording carcass identity, ante- and post-mortem inspection outcomes, and initial chilling conditions. Primary cutting and packing units generate the first batch identifiers and apply downstream labels. A centralized traceability database hosted either locally or in the cloud stores batch identities, time–temperature records, sanitation logs, operator metadata, and process-location stamps.

Cold transport, distribution warehouses, and secondary processing units (including grinding, slicing, and retail backroom operations) append additional records while preserving parent–child batch relationships. Retail receiving, storage, display, and repackaging constitute the final data capture nodes before products reach consumers. Importantly, return, recall, and waste-disposal events are recorded within the same system to maintain traceability continuity and enable effective backward investigation during quality or safety incidents.

As illustrated in Figure 7, the batch genealogy follows a hierarchical tree structure in which each downstream transaction appends new event data to an existing child batch without breaking its digital linkage to the original parent carcass ID. This cumulative, event-based recording model ensures that all movements, transformations, and post-sale actions remain embedded within a continuous lineage chain, preserving both backward and forward traceability throughout the product lifecycle.

The traceability process begins at the slaughterhouse level, where carcass identity, inspection outcomes, and initial chilling conditions are recorded. These records form the parent batch within the system. Subsequent handling stages including cold storage, refrigerated transport, and distribution append temperature exposure and movement data while preserving the original batch linkage. This approach directly responds to FMECA findings that identified loss of identity and undocumented temperature deviations as dominant quality risks in downstream operations.

At the retail stage, the figure highlights critical transformation points such as in-store weighing, repacking, and display. These steps were previously identified as high-risk nodes for traceability discontinuity, as new retail labels are often applied without reference to upstream batch information. In the proposed architecture, each retail pack is assigned a consumer-facing QR code that remains digitally linked to its parent batch, enabling continuity between slaughterhouse records and retail-level products.

The QR code functions as an interface rather than a data repository. Scanning the code allows authorized users and potentially consumers to access a concise summary of origin, post-slaughter handling history, and basic cold-chain compliance without exposing sensitive operational details. In this way, the system balances transparency with feasibility and data protection.

Effective traceability does not require continuous automation or advanced infrastructure at every node. Instead, it relies on preserving minimal but critical data elements across transformation stages, consistent with the FMECA-based prioritization of risks related to identity loss, temperature instability, and undocumented handling. By visualizing traceability as a flow of information that follows physical product movement, the figure reinforces the study's central argument that digital traceability should function as an operational quality management tool rather than a passive documentation system.

Although no Internet of Things (IoT) sensors, RFID infrastructure, or blockchain technologies were implemented in this initial phase, the underlying data model is intentionally designed to be technology ready. Temperature loggers, RFID tags, and distributed ledger technologies can be integrated in subsequent development stages without requiring fundamental redesign of the database architecture. This approach allows gradual technological upgrading while maintaining continuity in traceability structure.

From a conceptual standpoint, the prototype aligns with the three traceability models defined: (1) sequential information transfer between adjacent actors, (2) mutual information sharing among all actors, and (3) centralized coordination through a third-party data system. The present design corresponds most closely to the third model, functioning as a centralized data layer that integrates information from slaughterhouses, processors, distributors, and retailers into a unified, batch-oriented system [14].

Within the beef sector, traceability is commonly divided into live-animal traceability and meat traceability [15]. Live-animal traceability primarily supports disease control and herd management, whereas meat traceability addresses post-slaughter product flows and quality preservation. This study is explicitly positioned within the latter domain. The prototype operationalizes core traceability dimensions external, internal, chain, backward, and forward traceability. Internal traceability is reinforced at the facility level through batch-to-process linkage, while external traceability is preserved through consistent batch identifiers across organizations. Chain traceability is achieved through batch genealogy, and backward and forward traceability are enabled from retail packs to slaughter-level records and from source batches to affected consumer units.

The system architecture further supports traceability principles by defining how traceability information is collected, harmonized, and maintained across products, actors, and locations, and by ensuring that data continuity is preserved as products are transformed and distributed [15]. These principles are operationalized through standardized data categories, batch genealogy, and structured process logs that can be consistently adopted from slaughterhouse to retail environments.

Computer-Based Information Systems (CBIS) constitute the technological foundation of modern traceability, integrating hardware, software, dataware, netware, infoware, and brainware. The present prototype operates primarily at the intersection of dataware and infoware. In this implementation context, dataware refers to the structured capture, storage, and maintenance of raw traceability datasets, including batch identifiers, transformation records, temperature logs, sanitation verification entries, transport documentation, and recall events. It ensures data integrity, continuity, and retrievability across parent–child batch relationships. In contrast, infoware denotes the transformation of these structured datasets into interpretable, decision-oriented outputs, such as temperature threshold alerts, sanitation compliance summaries, recall trace-back lists, batch genealogy visualization, and consumer-facing QR-based information displays. While dataware preserves lineage and auditability at the database level, infoware enables operational intelligence and governance-oriented decision support. At the same time, the system is intentionally designed to remain implementable in environments with limited technological readiness, allowing gradual progression from basic data recording toward more advanced analytics and automated alerts.

Previous work [1] established a national digital traceability architecture for livestock identification and supply-chain information management, demonstrating that traceability enhances consumer trust and purchase intention. However, the present study indicates that traceability breakdowns occur primarily after slaughter rather than at the livestock registration stage. Routine batching practices, carcass fragmentation, secondary processing, and retail relabelling disrupt information continuity precisely at the points where FMECA identifies the highest quality risks.

Accordingly, the proposed prototype extends rather than replaces existing national traceability initiatives. It integrates traceability into the operational realities of post-slaughter handling and retail distribution, where quality degradation and consumer exposure are most likely to occur. By embedding time–temperature monitoring and sanitation verification within batch identity, the prototype transforms traceability from a record-keeping function into a quality governance mechanism.

In summary, the baseline digital traceability prototype offers a pragmatic, scalable, and quality-oriented interpretation of traceability for Indonesia's beef sector. It embodies FMECA findings within a conceptually robust yet technically accessible framework and establishes continuity between upstream livestock identification and downstream retail operations. The design positions digital traceability not merely as a transparency tool, but as a core component of operational quality control within modern meat supply chains. The prototype remains conceptual and was evaluated through scenario-based workflow simulation and expert walkthrough, without live operational deployment.

This study has several limitations. First, field observations were limited to four facilities and may not fully represent the diversity of Indonesia's beef supply chain. Second, FMECA scoring relied on expert judgment in the absence of longitudinal failure data, which may introduce contextual subjectivity despite structured consensus procedures. Third, the proposed prototype remains conceptual and has not yet undergone multi-site operational piloting or performance evaluation. Future research should focus on empirical deployment across multiple retail chains, usability testing, and quantitative assessment of traceability performance improvements following system implementation.

Table 3. Core data elements in the baseline digital traceability prototype

Category	Example Fields (Minimum Set)
Batch identity & origin	Global Batch ID, Parent Batch ID, product type/cut (e.g. loin, shank, ground), source slaughterhouse, supplier/agent ID, processing date
Process & location	Process step (slaughter, cutting, grinding, packing, retail repack), facility/unit name, location code, actor role (RPH, agent, retailer)
Time & temperature (CCP)	Start/end time, in/out temperature, storage type (chilled/frozen), transport duration, temperature deviation flag
Retail & consumer interface	Retail code, display date, expiry/best-before date, storage condition at display, QR code
Event & recall link	Complaint ID (if any), recall flag, return/disposal record

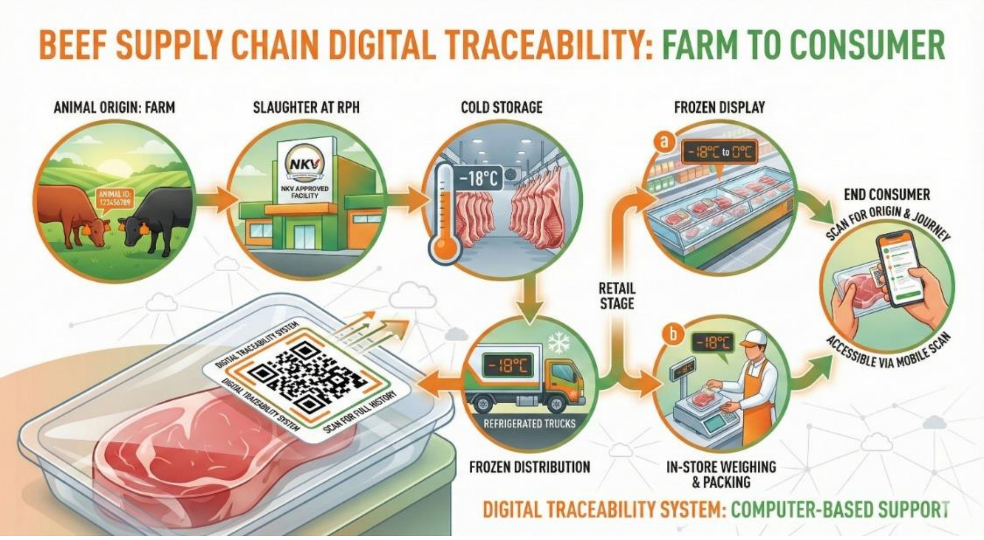

Fig. 5. Conceptual architecture of the baseline digital traceability prototype for Indonesia's post-slaughter beef cold chain, illustrating parent–child batch tracking from slaughterhouse operations through cold storage, distribution, retail handling, and consumer-facing QR code access. The prototype remains conceptual and was evaluated through scenario-based workflow simulation and expert walkthrough rather than live operational piloting. The diagram depicts a hierarchical one-to-many batch genealogy structure in which each carcass (parent batch) generates successive child batches across transformation stages while preserving backward and forward traceability.

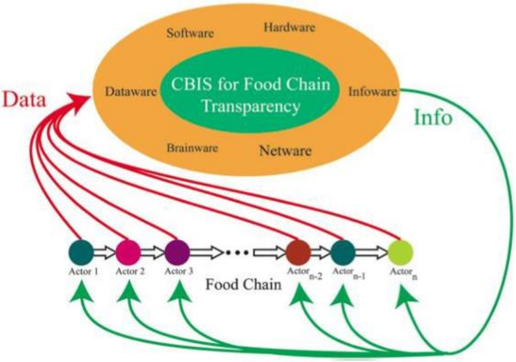

Fig. 6. Computer-Based Information System (CBIS) framework for food supply chain transparency [1], illustrating the integration of hardware, software, dataware, netware, infoware, and brainware. In the context of this study, dataware refers to the structured capture and storage of raw traceability data (e.g., batch IDs, temperature logs, sanitation records), while infoware denotes the transformation of these datasets into decision-oriented outputs such as alerts, compliance summaries, recall lists, and consumer-facing QR-based information displays.

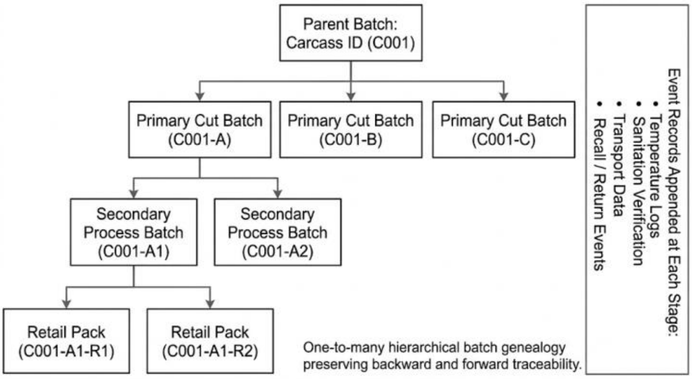

Fig. 7. Conceptual parent–child batch genealogy model of the proposed digital traceability prototype, illustrating hierarchical one-to-many inheritance from carcass-level parent batches to successive child batches across processing, distribution, and retail stages. The structure preserves continuous backward and forward traceability through explicit digital linkages at each transformation node.

4 Conclusion

This study confirms that Indonesia's primary traceability breakdown occurs after slaughter, where identity continuity and quality visibility deteriorate from carcass breakdown through secondary processing to retail repackaging. Supply-chain mapping reveals a fragmented, multi-path distribution structure that enables batch overwriting, inconsistent temperature monitoring, and weak sanitation documentation, particularly at downstream nodes. Consistent with these structural findings, FMECA analysis identified 7 of 15 operational nodes (47%) as high-risk (Unacceptable), with the highest criticality concentrated in secondary processing and retail operations. Identity loss, temperature deviation, and undocumented handling emerged as the dominant failure modes. To address these vulnerabilities, this study proposes a baseline digital traceability prototype grounded in parent–child batch logic and systematic capture of risk-relevant data, including temperature exposure, sanitation verification, and process metadata. By preserving hierarchical batch genealogy across transformation stages, the architecture reframes traceability from a transactional recording tool into an operational quality governance mechanism. The prototype remains conceptual and was evaluated through scenario-based workflow simulation and expert walkthrough, without live operational piloting. The batch genealogy model illustrates a one-to-many inheritance structure in which each carcass generates successive child batches while retaining backward and forward traceability. From an information systems perspective, this study advances a risk-driven traceability framework that integrates FMECA-based prioritization with batch-oriented system architecture. By aligning traceability design with operational risk concentration, the framework responds to recent calls for governance-oriented traceability models in agri-food supply chains. Policy implications include the need for standardized post-slaughter batch coding, minimum digital quality data requirements beyond slaughterhouses, and stronger regulatory oversight at retail-level traceability nodes. Such measures would enhance recall effectiveness, improve consumer protection, and restore visibility over handling conditions at the point of sale. More broadly, by embedding quality risk management within digital traceability design, this study contributes to SDGs 2, 9, and 12 through strengthened food safety governance, improved transparency, and greater resilience in Indonesia's beef supply chain.

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