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Iot-Enabled Dairy Systems: From Sensing And Data Integration To Operational Evaluation

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ABSTRAK

Penerapan Internet of Things (IoT) pada peternakan sapi perah berkembang pesat, namun literatur masih didominasi pendekatan berbasis komponen yang belum terintegrasi secara operasional. Penelitian ini mensintesis kajian IoT-based dairy farming systems melalui perspektif sistem end-to-end yang menghubungkan tujuan penerapan, sensing, integrasi data, kecerdasan, keluaran operasional, dan evaluasi penggunaan. Kajian dilakukan melalui systematic literature review terhadap 38 artikel terindeks Scopus periode 2020–2024 dengan pendekatan PRISMA. Hasil sintesis menunjukkan bahwa literatur mengarahkan penerapan IoT terutama pada performa operasional dan indikator kualitas awal, kondisi lingkungan kandang, kesehatan dan kesejahteraan ternak, serta efisiensi operasional dan pengelolaan sumber daya. Meskipun sensing relatif matang pada tingkat komponen, sebagian besar sistem masih bersifat monitoring-oriented dan berfungsi sebagai decision support, dengan keterbatasan integrasi dan otomasi. Kontribusi studi ini terletak pada penyajian kerangka konseptual sistemik yang menegaskan kesenjangan antara kapabilitas teknologi dan kesiapan operasional.

ABSTRACT

The adoption of Internet of Things (IoT) technologies in dairy farming has expanded rapidly, yet the literature remains dominated by isolated technological components rather than operationally integrated systems. This study synthesizes research on IoT-based dairy farming systems through an end-to-end system perspective linking system purposes, sensing, data integration, intelligence, operational outputs, and evaluation. A systematic literature review was conducted on 38 Scopus-indexed articles published between 2020 and 2024 following the PRISMA protocol. The synthesis indicates that IoT applications are primarily oriented toward operational performance and initial quality indicators, barn environmental monitoring, animal health and welfare management, and operational efficiency and resource management. Although sensing technologies are relatively mature at the component level, most systems remain monitoring-oriented and support decision-making mainly through notifications and early warnings, with limited automation and operational evaluation. This review contributes a system-level conceptual framework that highlights the gap between technological capability and operational readiness, guiding the development of more coherent and operationally meaningful IoT applications in dairy farming.

INTRODUCTION

Contemporary dairy production faces increasing pressure not only to improve milk yield, but also to ensure that production data and initial milk quality indicators are captured, interpreted, and used in a timely and integrated manner. In many dairy operations, records of milk volume and initial quality parameters such as temperature and pH are still collected manually or managed through loosely connected digital tools. As a consequence, these data are rarely transformed into actionable inputs for farm-level planning, quality assurance, or regional supply coordination. This situation highlights a persistent disconnect between data generation at the point of production and its systematic use in broader management processes.

The rapid diffusion of Internet of Things technologies has been widely regarded as a promising response to this challenge. Across the 38 Scopus-indexed studies synthesized in this review, IoT-enabled dairy systems demonstrate notable progress in distributed sensing, particularly for monitoring milk production, initial milk quality, barn environmental conditions, and animal health and behavior. However, the literature also reveals a consistent tendency to address these capabilities in isolation. Most studies emphasize individual components such as sensors, communication infrastructures, or analytics models, while paying limited attention to how these elements are integrated into coherent operational systems that support decision-making and long-term use.

This fragmented orientation is explicitly illustrated in Figure 1, From Fragmented IoT Applications to an End-to-End System Perspective in Dairy Studies. As shown in the figure, existing IoT dairy research predominantly clusters around sensing-oriented studies, communication and platform development, and analytics or artificial intelligence applications, with operational outputs typically limited to notifications or early warnings. Although these contributions demonstrate technological feasibility, they rarely articulate a complete system flow that connects sensing, data integration, intelligence, operational actions, and evaluation. The figure therefore positions this review as a deliberate shift toward an end-to-end system perspective that foregrounds integration and operational readiness rather than isolated technological performance.

Several recurring limitations identified in the reviewed literature help explain why this fragmentation persists. High implementation and maintenance costs frequently emerge as barriers that prevent farmers from adopting more sophisticated and integrated IoT solutions, particularly in small and resource-constrained contexts (Akbar et al., 2020; Ali & Mahmood, 2024). In addition, inadequate infrastructure and limited user training are repeatedly reported as factors that constrain effective system deployment. Many IoT applications are designed with limited consideration of existing farm workflows, which contributes to user resistance and ultimately undermines integration efforts (Engelberts et al., 2021; Jafri et al., 2024).

The literature further highlights a distinction between technological capability and actual operational use. While advanced sensing, analytics, and artificial intelligence techniques are shown to improve efficiency and productivity under controlled or experimental conditions, their uptake in everyday farming practice remains uneven. Farmers often perceive IoT systems as complex or insufficiently supported, leading to reluctance in sustained use despite demonstrated technical benefits (Erdem & Agir, 2024; Subash et al., 2021)). This recurring gap between available technological capability and realized operational value underscores the importance of system designs that prioritize integration with routine agricultural practices, supported by appropriate training and financial mechanisms (Arago et al., 2022; Erdem & Agir, 2024).

Closely related to this gap is the distinction frequently discussed in IoT dairy research between monitoring-oriented systems and operationally actionable systems. Monitoring-oriented implementations primarily collect and report data on animal health, milk production, or environmental conditions, offering visibility without automatic intervention (Tangorra et al., 2024). In contrast, a smaller subset of studies reports systems capable of translating data into real-time decisions and actions, such as adaptive feeding strategies or targeted veterinary interventions (Cabrera et al., 2020). The ability to move from passive monitoring to active management is consistently identified as a critical requirement for improving operational efficiency and system relevance at the farm level (Behjati et al., 2021; Navarro et al., 2020).

Despite these advances, clear gaps remain in connecting milk production and initial quality data to comprehensive management processes. The reviewed studies indicate that data from milking, feeding, health monitoring, and environmental sensing are often analyzed separately, limiting the generation of holistic insights that align with broader farm objectives (Navarro et al., 2020). As emphasized by (Cabrera et al., 2020), this fragmentation constrains strategic planning and reduces the potential of IoT systems to systematically optimize both production efficiency and milk quality.

Importantly, a growing subset of IoT dairy studies frames these systems as socio-technical rather than purely technical solutions. This perspective recognizes that system performance depends not only on sensors and algorithms, but also on human actors, organizational practices, and institutional contexts. Prior work highlights how cooperative arrangements and stakeholder interactions shape the effectiveness of technology adoption in the dairy sector, reinforcing the need to consider social structures alongside technological design (Daniell et al., 2020). Nevertheless, even within this socio-technical framing, the literature reveals persistent gaps in aligning milk production and quality data with collaborative decision-making and integrated management practices. Fragmented data streams, limited user engagement, and weak integration between technological and human elements continue to hinder the development of holistic and operationally meaningful IoT-enabled dairy systems (Amiri-Zarandi et al., 2022; Marković et al., 2024).

Taken together, these patterns motivate the central focus and objectives of this systematic literature review. Rather than cataloging individual IoT applications, this study aims to synthesize prior work through an end-to-end system lens that connects sensing, data integration, intelligence, operational outputs, and evaluation. By doing so, the review explicitly addresses the gap between technological capability and operational readiness that characterizes much of the existing IoT-enabled dairy literature, as conceptually positioned in Figure 1.

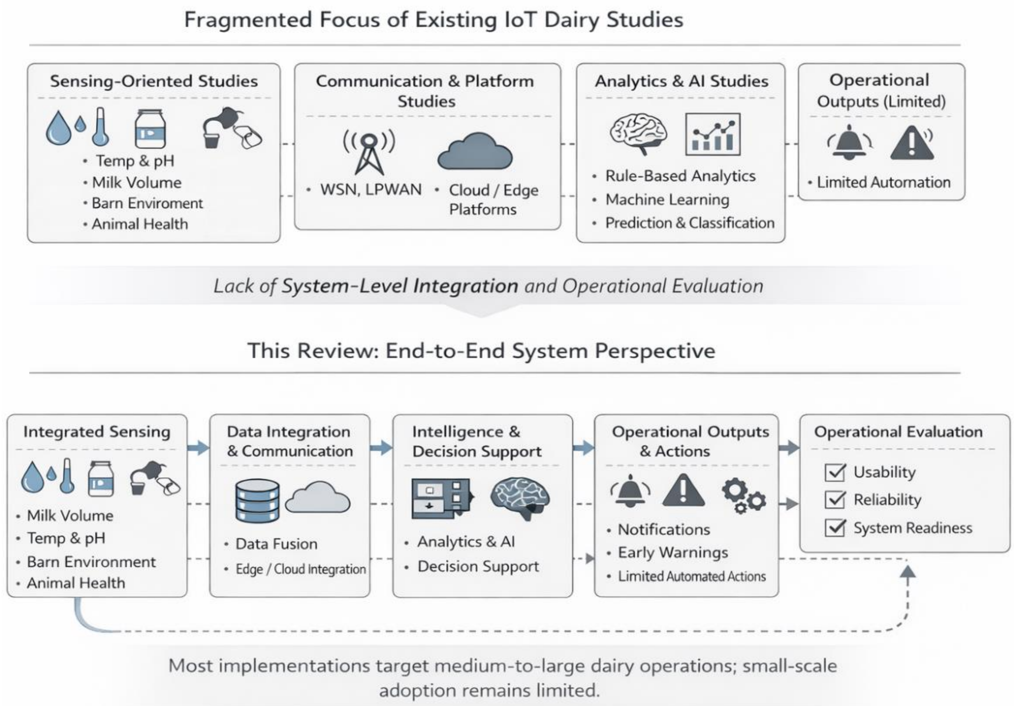

Figure 1. From Fragmented IoT Applications to an End-to-End System Perspective in Dairy Studies

Figure 1 illustrates the research positioning and core argument of this systematic literature review on IoT-enabled dairy systems. Based on the synthesis of 38 Scopus-indexed studies, existing literature predominantly addresses IoT in dairy through fragmented technological approaches, including isolated sensing applications, communication and platform development, and analytics or artificial intelligence models, with operational outputs often limited to notifications or early warnings. While sensing commonly targets milk production parameters, initial milk quality, barn environmental conditions, and animal health, these components are rarely integrated into a coherent end-to-end operational system. In contrast, this review adopts a system-level perspective that conceptually connects sensing, data integration and communication, intelligence-driven decision support, operational outputs, and operational evaluation, thereby highlighting the gap between technological capability and operational readiness in current IoT-enabled dairy research.

THEORETICAL BACKGROUND

IoT as a Layered and Socio-Technical System in Dairy Contexts

The literature on IoT-enabled dairy systems increasingly conceptualizes IoT not as a collection of smart devices or isolated data pipelines, but as a layered system in which multiple functional components interact to support agricultural operations. This view is particularly salient in dairy contexts, where production performance, initial milk quality, and animal welfare are closely interrelated and must be addressed concurrently (Herde et al., 2020; Kilani et al., 2022). Core system layers commonly discussed include sensing, communication, data integration, intelligence, action, and evaluation, with system value emerging from their coordinated operation rather than from individual technologies in isolation.

This layered conceptualization is frequently embedded within a socio-technical perspective. Rather than treating IoT systems as purely technical artifacts, several studies emphasize the need to align technological layers with human decision-making, organizational routines, and institutional settings (Daniell et al., 2020; Kilani et al., 2022). From this standpoint, effective IoT integration depends not only on sensor accuracy or analytics performance, but also on how information flows across layers and is embedded in cooperative and managerial processes within dairy operations.

Attention to System Layers in Existing IoT Frameworks

Despite broad agreement on the layered nature of IoT systems, existing frameworks vary considerably in how explicitly individual system layers are addressed. The sensing and communication layers receive the most consistent attention, reflecting their foundational role in data acquisition and transmission (Siddiqui, 2022). In contrast, data integration and evaluation layers are less frequently articulated, resulting in limited discussion of how heterogeneous data streams are synthesized and how system outcomes are assessed beyond initial deployment.

The intelligence and action layers occupy an intermediate position in the literature. Studies focusing on analytics, artificial intelligence, or automation often describe decision-support mechanisms and, in some cases, system-initiated actions. Pattern recognition with convolutional neural networks enables robust high-level inference from non-verbal multi-modal sensory data under challenging conditions, supporting automated decision-support systems across domains (Utami et al., 2019, 2022).

However, these contributions frequently rely on implicit assumptions about upstream data integration and downstream evaluation, leaving the connection between intelligent processing and sustained operational impact weakly theorized, particularly in relation to the use of production and quality metrics for farm management (Pigina et al., 2024).

End-to-End Operation and Breakpoints in IoT-Enabled Dairy Systems

End-to-end operation in IoT-enabled dairy systems is generally defined as a continuous flow of data from initial sensing through integration and analysis to operational outputs, including alerts, recommendations, or automated adjustments (Baldoni et al., 2023). From this perspective, end-to-end systems are distinguished not by the sophistication of individual algorithms, but by the continuity that links data collection, processing, and use across system layers. Systems-oriented theoretical models conceptualize this continuity by emphasizing interactions among technical components and user roles within interconnected IoT architectures, where data move across sensing nodes, communication infrastructures, and decision-making modules under operational constraints such as reliability and Quality of Service (Montazerolghaem & Yaghmaee, 2020; Murillo et al., 2020). Despite this conceptual ideal, the literature consistently identifies practical breakpoints in end-to-end chains, with dashboard-centric and alert-based systems often functioning as terminal points. In such cases, insights generated by sensing and analytics are not systematically translated into operational decisions or actions, thereby limiting the contribution of IoT systems to everyday dairy farm management (Akbar et al., 2020).

Sensing Constructs for Production, Quality, and Animal Welfare

Sensing parameters play a central role in how production performance and initial milk quality are represented within IoT-enabled dairy systems. Milk volume, temperature, and pH are frequently employed as proxies due to their relevance to food safety, processing suitability, and economic value, with strong links to microbial activity, spoilage risk, and the physiological condition of dairy cows (Ajitha et al., 2023; Mirzabekyan et al., 2024; Nguyen et al., 2024). Across the literature, these metrics are treated inconsistently: some studies integrate them as operational inputs to support real-time adjustments in feeding, handling, or health management, while others use them primarily as descriptive indicators of system performance (Lovarelli et al., 2020; Nogara et al., 2023).

Environmental sensing extends this theoretical linkage by situating production and quality monitoring within broader considerations of animal welfare. Parameters such as barn temperature, humidity, and air quality are consistently associated with animal comfort, stress mitigation, and productivity, reinforcing environmental monitoring as an integral component of system-level performance (Blanco-Penedo et al., 2020). At the same time, many studies implicitly assume adequate performance from low-cost sensing devices, even as concerns regarding calibration stability, data accuracy, and long-term reliability under field conditions are frequently acknowledged, with potential implications for downstream analytics and decision-making (Ajitha et al., 2023).

Operational Use and Evaluation of IoT Systems in Dairy Farming

Operational use is commonly defined as the extent to which IoT technologies are embedded in daily farm activities and support routine decision-making related to production efficiency, animal health, and environmental control (Akbar et al., 2020; Arago et al., 2022). This definition emphasizes seamless integration with existing workflows and the use of real-time data to enable timely interventions, positioning operational use as a critical bridge between technical capability and everyday farm management.

Evaluation practices are typically discussed in terms of usability, reliability, and system integration, which together shape acceptance and effectiveness in operational settings (Gehlot et al., 2022; Hassoun et al., 2023). Across the reviewed studies, however, evaluation remains largely focused on short-term technical validation, with limited attention to sustained use, organizational fit, and system evolution over time. These recurring patterns indicate that operational use and evaluation are conceptually acknowledged but unevenly articulated across system layers, a gap that motivates the synthesis of core theoretical constructs summarized in Table 1.

Table 1. Theoretical Constructs in IoT-Enabled Dairy Systems

Theoretical Construct	Description	Relevance to IoT-Enabled Dairy Systems	Operational Implications
Distributed Sensing	Use of heterogeneous sensors to capture production, quality, environmental, and animal-related data	Forms the primary data layer in most IoT dairy studies, especially for milk production, initial quality, and barn conditions	Enables continuous monitoring but often remains fragmented without system-level integration
Data Integration	Aggregation and synchronization of multi-source IoT data across platforms	Determines whether isolated sensor data can be transformed into coherent system information	Limits or enables cross-parameter analysis for operational decision-making
Communication Infrastructure	Mechanisms for transmitting data between sensors, gateways, and platforms	Supports real-time or near-real-time data flow in dairy operations	Affects system reliability, latency, and scalability in operational settings
Computational Intelligence	Application of rule-based logic, analytics, or AI/ML to interpret IoT data	Widely used for prediction, classification, and anomaly detection in dairy contexts	Shifts systems from passive monitoring to decision-support capabilities
Decision Support	Translation of processed data into actionable information	Acts as the interface between technical systems and human operators	Mostly results in alerts or early warnings rather than direct operational control
System Automation	Execution of system-initiated actions based on IoT outputs	Present in a limited number of studies, often at prototype level	Indicates emerging movement toward closed-loop dairy systems
Operational Evaluation	Assessment of system use, reliability, and integration with workflows	Rarely reported explicitly in primary studies	Constrains understanding of long-term usability and system readiness
User Context and Scale	Characteristics of dairy operations adopting IoT systems	Most implementations target medium-to-large farms	Highlights adoption barriers and transferability to small-scale operations

Table 1 synthesizes the dominant theoretical constructs recurring across the 38 Scopus-indexed IoT-enabled dairy studies reviewed in this SLR. Across these studies, IoT-enabled dairy systems are primarily grounded in distributed sensing architectures that capture milk production indicators, initial milk quality parameters, barn environmental conditions, and animal-related variables, supported by heterogeneous communication infrastructures and platform-based data handling. However, data integration across system components is frequently partial, resulting in siloed information flows and monitoring-oriented operational views rather than fully integrated decision-making systems (Akbar et al., 2020; Pigina et al., 2024). While computational intelligence is widely applied for prediction and anomaly detection, its operational role remains largely confined to decision support, with automation and closed-loop control reported only in a limited subset of pilot-level implementations. Taken together, these recurring constructs reveal a persistent gap between technological capability and operational readiness in current IoT-enabled dairy systems.

RESEARCH METHODOLOGY

Review Design and Strategy

This study adopts a systematic literature review (SLR) design to synthesize empirical research on IoT-enabled dairy systems from a system-level and operational perspective. The methodological approach is informed by prior SLRs on IoT applications in agriculture, which commonly combine structured search strategies with qualitative synthesis to capture both technological patterns and contextual implementation insights (Bajaj et al., 2021; Doshi & Hiran, 2023). This study adopts a systematic literature review approach to synthesize empirical studies on IoT-enabled dairy systems. Accordingly, the review focuses on how sensing, data integration, communication, intelligence, operational outputs, and evaluation are articulated across empirical studies, while remaining attentive to reported implementation contexts and user scales.

Data Sources and Search Strategy

The literature search was conducted exclusively using the Scopus database to ensure coverage of peer-reviewed and internationally indexed studies. A structured keyword query combining IoT-related terms (e.g., “Internet of Things”, “IoT-enabled”, “IoT-based”) with dairy-related terms (e.g., “dairy”, “dairy farming”, “dairy systems”, “dairy production”) was applied. The search strategy was designed to capture studies that explicitly position IoT as part of a system within dairy contexts, rather than as isolated sensing or algorithmic components. Consistent with recent SLR practices in agricultural IoT research, the search was restricted to journal and conference articles published in English within the 2020–2024 period to reflect contemporary IoT architectures and deployment practices (Arena et al., 2022; Doshi & Hiran, 2023).

Inclusion and Exclusion Criteria

Studies were included if they investigated IoT-enabled systems in dairy contexts with a clear focus on sensing, data integration, communication platforms, system operation, or operational evaluation. Eligible publications were peer-reviewed journal or conference articles written in English and providing sufficient methodological and system-level detail to support qualitative analysis. In line with recommendations from prior agricultural IoT reviews, inclusion did not require full system automation or long-term evaluation, as long as studies explicitly framed their contributions within an IoT system context (Bajaj et al., 2021). Studies were excluded if they focused solely on biological, chemical, or material-level analyses, addressed non-dairy livestock or agricultural domains, emphasized algorithmic or communication optimization without operational system context, or constituted review or conceptual papers without empirical implementation (Hassan et al., 2020; Quý et al., 2022).

Screening and Selection Process

The screening and selection process followed PRISMA guidelines to ensure transparency and reproducibility. As illustrated in Figure 2, the initial Scopus search identified 459 records. After applying a publication year filter (2020–2024), 274 records remained. Subsequent filtering by document type (articles only) and language (English) reduced the dataset to 91 records. Subject-area filtering further narrowed the pool to 52 studies relevant to applied IoT, computer science, engineering, and agricultural domains. Title and abstract screening based on the predefined inclusion and exclusion criteria resulted in the exclusion of 14 records, yielding a final set of 38 studies for qualitative synthesis. These studies constitute the empirical basis for analyzing system purposes, sensing configurations, data integration approaches, intelligence use, operational outputs, and evaluation practices in IoT-enabled dairy systems.

Figure 2 summarizes the PRISMA-based screening process that resulted in the final set of 38 Scopus-indexed studies included for qualitative synthesis. An initial search of the Scopus database using predefined IoT- and dairy-related keywords identified 459 records. After applying a publication year filter (2020–2024), 274 records remained, which were subsequently refined by document type (articles only) and language (English), resulting in 91 records. Further filtering based on relevant subject areas reduced the dataset to 52 articles. Abstract screening was then conducted using predefined inclusion and exclusion criteria focusing on IoT-enabled dairy systems with empirical or applied relevance, leading to the exclusion of 14 records. The final set of 38 articles was included for qualitative synthesis, forming the empirical basis for analyzing system purposes, sensing technologies, data integration, intelligence, operational use, and evaluation patterns in IoT-enabled dairy research.

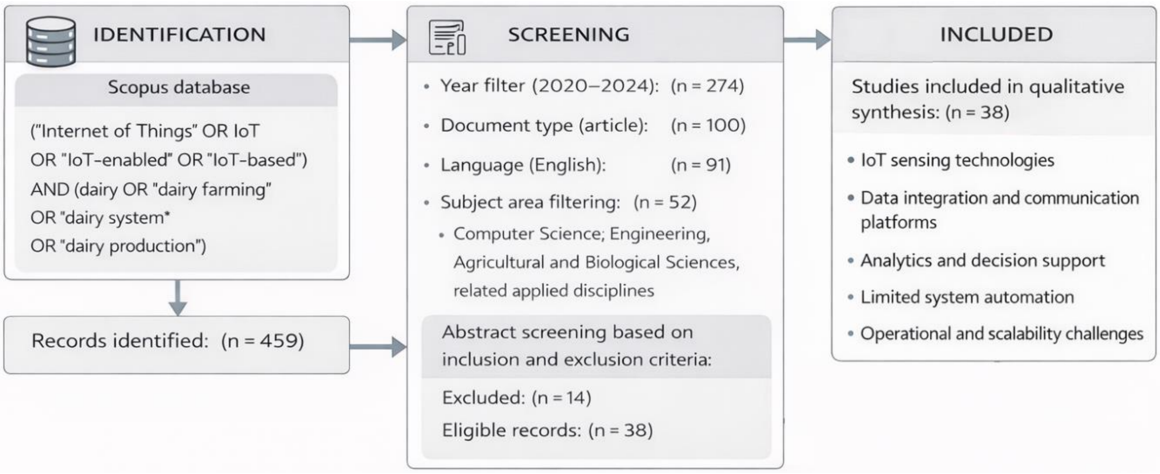

Figure 2. PRISMA Flow Diagram

RESULTS AND DISCUSSION

Results

The results synthesize recurring system-level patterns across 38 Scopus-indexed studies on IoT-enabled dairy systems, highlighting how these systems are collectively designed, implemented, and evaluated in practice. Rather than enumerating individual study outcomes, the synthesis traces common configurations spanning sensing, data integration, intelligence, operational use, and system readiness. Within this landscape, milk volume and initial milk quality function as salient entry points for examining system design, while remaining representative rather than exhaustive of the sensing scope addressed in the literature.

Purposes, User Scale, and Sensing Technologies in IoT-Enabled Dairy Systems

According to the reviewed studies, IoT-enabled dairy systems primarily target milk production monitoring, initial milk quality assessment, barn environmental monitoring, and animal health and behavior tracking (Akbar et al., 2020; Cabrera et al., 2020). These purposes are predominantly implemented in medium- and large-scale dairy operations, reflecting greater infrastructure readiness and investment capacity, whereas small-scale deployments remain limited and are largely confined to pilot or experimental settings.

Sensing technologies predominantly rely on low-cost microcontroller-based platforms, such as Arduino and ESP devices, integrated with flow sensors, load cells, temperature sensors, pH probes, environmental sensors, and wearable devices (Ajitha et al., 2023; Nguyen et al., 2024). Milk volume and initial quality parameters are widely monitored at milking, storage, or collection points. Despite the technical maturity of these sensing components, their use remains largely monitoring-oriented, with limited integration into operational decision-making. Only a smaller subset of studies extends sensing toward feeding, resource management, and operational efficiency, mainly in large-scale operations where programmable logic controllers and embedded systems support integrated farm management platforms. A structured overview of system purposes, user scales, and sensing components is detailed in Table 2.

Table 2. Purposes, User Scale, and Sensing Components in IoT-Enabled Dairy Systems

System Purpose	User Scale	Device Type	Sensor Type	Measured Parameters	Implementation Context
Milk production monitoring	Medium to large	Arduino, ESP	Flow sensors, load cells	Milk volume, milking duration	Automated or semi-automated milking systems at farm level
Initial milk quality monitoring	Medium	Arduino, ESP	Temperature sensors, pH sensors	Milk temperature, pH	Post-milking quality checks at collection or storage points
Barn environmental monitoring	Medium to large	ESP, PLC	Temperature, humidity, gas sensors	Ambient temperature, humidity, ammonia	Indoor barn monitoring for animal comfort and welfare
Animal health and behavior monitoring	Medium to large	Arduino, ESP	Wearable sensors, accelerometers	Activity level, movement patterns	Individual animal monitoring using collars or tags
Feeding and resource management	Large	PLC, embedded controllers	Weight sensors, proximity sensors	Feed intake, feeding frequency	Integrated feeding and herd management systems
Operational efficiency monitoring	Medium to large	Arduino, ESP	Multi-sensor nodes	Combined production and environment data	Decision support platforms for farm management

Communication, Architecture, and Data Integration in IoT Dairy Systems

Communication technologies in IoT-enabled dairy systems predominantly include wireless sensor networks, LPWAN solutions, WiFi, and cellular networks, selected according to farm scale, coverage requirements, and energy constraints (Montazerolghaem & Yaghmaee, 2020; Murillo et al., 2020). Smaller deployments commonly rely on local wireless sensor networks, whereas wider-area or multi-site implementations favor LPWAN or cellular connectivity. To accommodate these heterogeneous conditions, hybrid edge–cloud architectures are increasingly adopted to combine local preprocessing with centralized data storage and visualization.

Data integration is most often implemented through gateway-based aggregation and cloud platforms, enabling consolidation of heterogeneous sensor data across production, environmental, and animal-related domains (Akbar et al., 2020; Pigina et al., 2024). In practice, integration primarily supports data transmission and visualization rather than seamless interoperability across system components or management functions. Consequently, integration remains largely monitoring-oriented, with relatively few studies demonstrating cohesive data fusion that supports coordinated operational decision-making. A structured overview of communication technologies, architectures, data types, and integration mechanisms is consolidated in Table 3.

Table 3. Communication, Architecture, and Data Integration in IoT Dairy Systems

Communication Technology	System Architecture	Data Types	Integration Mechanism	Operational Purpose
Wireless Sensor Networks (WSN)	Edge	Environmental and animal data	Local aggregation at gateway nodes	Real-time monitoring of barn conditions and animal activity
LPWAN (e.g., LoRa-based)	Hybrid (Edge–Cloud)	Production and environmental data	Periodic uplink to cloud platforms	Wide-area monitoring with low power consumption
WiFi	Cloud	Milk production and quality data	Direct transmission to cloud databases	Centralized data storage and visualization
Cellular networks	Cloud	Multi-source operational data	API-based data ingestion	Remote monitoring and management of distributed farms
WSN + WiFi	Hybrid	Sensor and control data	Edge preprocessing with cloud synchronization	Reduced latency for decision support
LPWAN + Cellular	Hybrid	Aggregated farm-level data	Gateway-mediated integration	Scalable data collection across multiple sites

Intelligence, Decision-Making, and System Actions in IoT Dairy Systems

Across the reviewed studies, intelligence in IoT-enabled dairy systems is predominantly implemented through rule-based logic and data analytics, generating notifications, early warnings, and operational recommendations for farmers, technicians, and farm managers (Navarro et al., 2020; Tangorra et al., 2024). These approaches primarily support situational awareness, routine monitoring, and short-term operational planning. More advanced artificial intelligence and machine learning techniques are increasingly reported, particularly for predictive alerts and anomaly detection in animal health and environmental monitoring.

Despite the growing use of predictive analytics, the operational role of intelligence remains largely confined to decision support rather than direct system control. Only a limited subset of studies reports automated actions through actuator-based control, typically restricted to pilot deployments or specific subsystems. Overall, intelligence in current IoT-enabled dairy systems functions mainly as an assistive layer that augments human decision-making rather than enabling fully autonomous operation. A structured overview of intelligence types, outputs, action levels, user actors, and operational impacts is outlined in Table 4.

Table 4. Intelligence, Decisions, and System Actions in IoT-Enabled Dairy Systems

Type of Intelligence	Output Form	Action Type	User Actor	Operational Impact
Rule-based logic	Notifications	Information only	Farmers, farm operators	Improves situational awareness for daily monitoring
Rule-based logic	Early warnings	Information only	Farmers, technicians	Supports timely response to abnormal conditions
Data analytics	Recommen-dations	Decision support	Farm managers	Assists planning of feeding, milking, and barn management
Data analytics	Early warnings	Information only	Farmers, veterinarians	Enables preventive intervention for health and welfare issues
AI and machine learning	Predictive alerts	Information only	Farm managers, advisors	Anticipates production or health risks
AI and machine learning	Automated actions	Actuator control	Automated systems, operators	Limited optimization of environmental or operational settings

Operational Evaluation and System Readiness across User Scales

Across the reviewed studies, operational evaluation practices in IoT-enabled dairy systems vary systematically with user scale. Small-scale farms are predominantly assessed through short-term usability-focused trials in pilot or experimental settings, emphasizing basic functionality and ease of use, with limited evidence of sustained adoption. Medium-scale implementations increasingly report evaluations of reliability and partial system integration, supporting routine monitoring while revealing persistent challenges in aligning IoT systems with daily farm workflows.

Large-scale dairy operations and enterprise-level systems exhibit more mature evaluation practices, with greater emphasis on reliability and infrastructure compatibility over mid- to long-term horizons. In these contexts, IoT platforms are often embedded within broader management systems, although evaluation remains focused on technical performance rather than user experience or organizational fit. Across all user scales, explicit long-term assessment of usability, socio-technical alignment, and sustained adoption is inconsistently reported, resulting in fragmented evidence of system readiness conditioned by implementation context (Espinoza-Sandoval et al., 2024; Gehlot et al., 2022). A structured overview of user scales, evaluation aspects, time horizons, and readiness-related findings is presented in Table 5.

Table 5. User Scale, Evaluation, and System Readiness in IoT-Enabled Dairy Systems

User Scale	Implementation Context	Evaluation Aspects	Evaluation Horizon	Key Findings
Small-scale farms	Pilot or experimental deployments	Usability	Short-term	Systems are mainly assessed for basic functionality and ease of use, with limited evidence of sustained adoption
Medium-scale farms	Operational farm environments	Usability, reliability	Short- to mid-term	IoT systems support routine monitoring, but integration with daily workflows is often partial

User Scale	Implementation Context	Evaluation Aspects	Evaluation Horizon	Key Findings
Medium-scale farms	Applied field trials	Reliability, integration	Mid-term	Performance stability is reported, while cross-system integration remains limited
Large-scale farms	Highly automated dairy operations	Reliability, integration	Mid- to long-term	Systems demonstrate higher operational stability and infrastructure compatibility
Large-scale farms	Enterprise-level management systems	Integration	Long-term	IoT platforms are embedded within broader management systems, though evaluation focuses more on technical performance than user experience

Table 5 synthesizes patterns observed across the reviewed studies, illustrating how operational evaluation practices and system readiness considerations differ by user scale in IoT-enabled dairy systems. Across the literature, small-scale deployments tend to rely on short-term, usability-oriented evaluations, whereas medium- and large-scale implementations more frequently emphasize system reliability and integration within operational environments. Notably, systematic long-term assessment of usability, organizational fit, and sustained adoption is inconsistently addressed across all scales. Overall, this synthesis suggests that system readiness evaluation in IoT dairy research remains fragmented and highly contingent on implementation context rather than guided by a unified evaluative framework.

Discussions

Integrated Discussion

The synthesis of the reviewed studies indicates that IoT-enabled dairy systems are predominantly oriented toward monitoring milk production and initial milk quality, barn environmental conditions, animal health and behaviour, and, to a lesser extent, operational efficiency. These purposes consistently emerge across the literature as primary entry points for IoT adoption, reflecting sector-wide priorities related to productivity, welfare, and risk mitigation rather than comprehensive farm-level optimization (Akbar et al., 2020; Cabrera et al., 2020; Navarro et al., 2020).

Across these applications, sensing technologies can be considered relatively mature at the component level, as evidenced by their stable and repeated use across diverse monitoring contexts. Low-cost sensors and microcontroller-based platforms reliably capture milk volume, temperature, pH, environmental parameters, and animal activity. However, this maturity at the sensing layer is not matched by equivalent advancement in intelligence and action. Most systems rely on rule-based logic, analytics, or predictive models to generate notifications, early warnings, and recommendations, while automated control and closed-loop actuation remain limited and context-specific (Pigina et al., 2024; Tangorra et al., 2024). As a result, IoT dairy systems largely function as decision-support tools rather than autonomous management systems.

Implementation patterns further show a strong concentration of IoT deployments at medium and large farm scales, where infrastructure availability, investment capacity, and operational complexity justify digital integration. Small-scale farms are comparatively underrepresented and tend to adopt isolated solutions focused on single parameters, often without robust integration or long-term evaluation (Espinoza-Sandoval et al., 2024; Gehlot et al., 2022). This uneven adoption highlights that the primary bottlenecks in IoT dairy development are not technological availability, but system coherence, integration across functional layers, and operational readiness.

Taken together, the cross-sectional synthesis reveals that measurements of milk volume and initial milk quality are frequently treated as standalone monitoring variables rather than as integral components of end-to-end systems. This observation directly motivates the system-level abstraction presented in Figure 3, which connects sensing, intelligence, operational actions, and evaluation within a unified conceptual flow. This fragmentation limits the potential of IoT systems to support coordinated production management and distribution planning, particularly beyond the individual farm level.

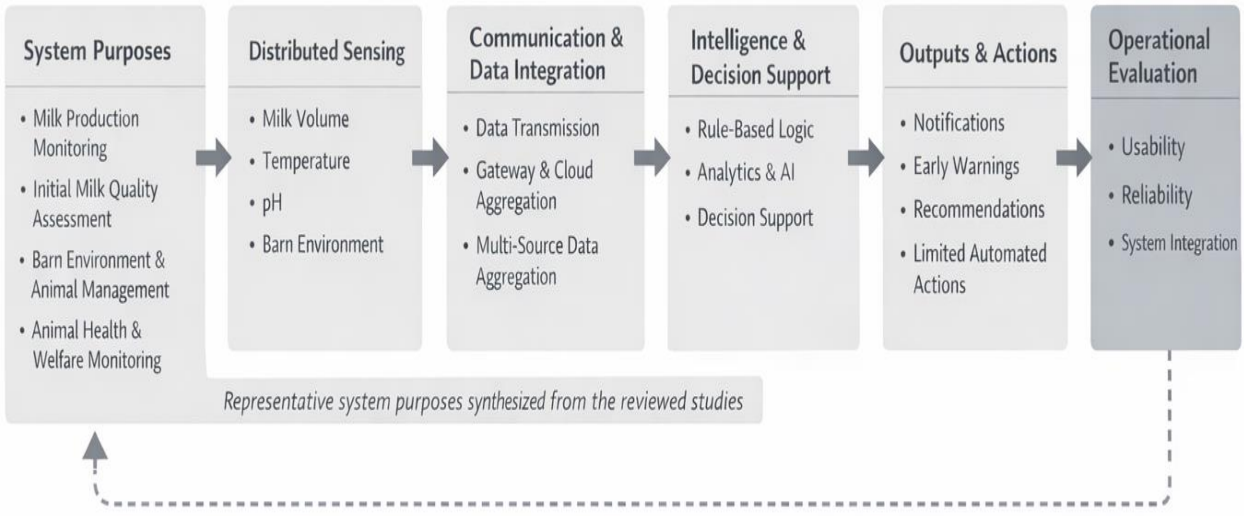

Figure 3. End-to-End Conceptual Framework of IoT-Enabled Dairy Systems

Figure 3 presents an end-to-end conceptual framework synthesizing how IoT-enabled dairy systems are structured across the reviewed studies. The framework situates dominant system purposes, such as milk production monitoring, initial milk quality assessment, barn environment and animal management, and health and welfare monitoring, as representative entry points rather than exhaustive applications. These purposes are operationalized through distributed sensing of production, physiological, and environmental parameters, which are subsequently transmitted and integrated via gateway- and cloud-based infrastructures. Intelligence layers apply rule-based logic, analytics, and, in fewer cases, artificial intelligence to generate notifications, early warnings, and recommendations. Consistent with the literature, automated actions appear only in limited subsystems or pilot contexts. The dashed feedback loop emphasizes that closed-loop operation and system-level readiness remain emerging features rather than established practices in current IoT dairy research.

Limitations, Future Research Directions, and Implications

Beyond the integrated synthesis, several limitations emerge consistently from the reviewed literature. A primary limitation concerns the inconsistent reporting of operational evaluation. While many studies demonstrate technical feasibility and short-term performance, systematic assessment of usability, organizational fit, and long-term adoption is rarely addressed, constraining the ability to assess sustained system effectiveness and readiness in real-world dairy operations (Gehlot et al., 2022). These limitations point directly to future research needs. Studies should move beyond treating milk volume and initial milk quality as isolated monitoring outputs and instead position them within integrated, data-driven planning systems that link production, distribution, and regional supply management. In addition, mid- to long-term operational evaluations are needed to examine not only technical reliability but also sustained use, user adaptation, and socio-technical alignment across diverse farm contexts (Espinoza-Sandoval et al., 2024).

From a theoretical perspective, the findings reinforce the value of adopting a systemic lens in IoT dairy research. Conceptualizing IoT-enabled dairy systems as interconnected socio-technical arrangements, rather than collections of individual technologies, offers a more coherent explanation of observed adoption patterns, integration challenges, and operational constraints. Practically, the synthesis suggests that the primary value of IoT-enabled dairy systems lies less in deploying additional sensors and more in improving system integration and operational alignment. For practitioners and policymakers, this underscores the importance of interoperable architectures and evaluation frameworks that support production management, quality assurance, and coordinated regional milk supply planning (Navarro et al., 2020).

CONCLUSION AND SUGGESTIONS

Conclusion

This systematic literature review synthesizes 38 Scopus-indexed studies to examine how IoT-enabled dairy systems are designed, implemented, and evaluated when viewed through an end-to-end system perspective. Rather than treating IoT as a collection of isolated technologies, the synthesis shows that existing studies consistently converge on a limited set of core purposes, namely milk production monitoring, initial milk quality assessment, barn environmental monitoring, and animal health and welfare management. These purposes function as dominant entry points for IoT adoption across dairy contexts, reflecting priorities related to productivity, risk mitigation, and operational visibility.

Across the reviewed literature, sensing technologies for capturing milk volume, temperature, pH, environmental conditions, and animal-related indicators appear relatively mature at the component level. However, this maturity is not matched by comparable progress in system integration, intelligence, and action. Most systems remain monitoring-oriented, relying on notifications, early warnings, and recommendations to support human decision-making, while automated or closed-loop control is limited to specific and experimental contexts. Consequently, IoT-enabled dairy systems continue to operate primarily as decision-support tools rather than as fully integrated operational systems, highlighting a persistent gap between technological capability and operational readiness.

Suggestions

Future research on IoT-enabled dairy systems should move beyond component-level innovation and explicitly address system-level integration and operational use. In particular, milk production volume and initial milk quality should be positioned not merely as monitoring outputs, but as actionable inputs within integrated, data-driven planning processes that support farm-level management and, where relevant, broader coordination. Such an orientation would strengthen the practical relevance of IoT systems and better align sensing capabilities with decision-making needs.

In addition, there is a clear need for more rigorous mid- to long-term operational evaluations across different farm scales. Future studies should assess usability, reliability, workflow integration, and sustained adoption, while accounting for socio-technical factors such as user training, organizational practices, and contextual constraints. From a practical standpoint, prioritizing interoperable architectures and coherent evaluation frameworks over the proliferation of new sensors or algorithms is likely to offer greater value for improving production management, quality assurance, and overall system readiness in contemporary dairy operations.

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