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Unlocking dairy traceability: Current trends, applications, and future opportunities

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ABSTRACT

Traceability is a transparent quality index in almost every supply chain. Especially when it comes to highly perishable products, such as dairy, the need for an effective traceability system is unavoidable due to increased fraudulent products, adulteration, excessive additives, and toxic substances. The dairy industry requires an effective traceability system that ensures visibility and transparency in the supply chain while enhancing safety, quality, and adherence to ethical standards; promotes consumer trust and stakeholder collaborations; optimizes dairy operations for economic benefits; and enables end-to-end tracking and monitoring of processes. By effectively utilizing resources and reducing wastage, the system supports the principal objectives of sustainable development through advancing reliability and constant advancements. This paper offers insights into the recent developments, trends, opportunities, and impacts of traceability implementation in the dairy industry. The theoretical and technological status of traceability was investigated, and the content analysis was used to examine the intervention of digital technologies in dairy traceability and sustainability indicators. The study highlights research indicators in different dairy domains, suggesting potential traceability research pathways. It also discusses past, present, and future aspects of traceability, along with challenges, advancements through digital technologies, and its implications for dairy stakeholders. The findings revealed that implementing an effective traceability system can help attain specific United Nations Sustainable Development Goals (UN SDGs).

1. Introduction

The supply chain connects various entities, including suppliers, transport companies, processing units, distribution partners, retailers, and consumers, to form a complicated network supply chain (Ageron et al., 2020). This complex chain involves numerous process phases, consuming significant time and integrating various locations. As a result, traceability becomes vital for the product's quality and safety concerns (Hao et al., 2020). The traceability technique, especially in supply chains, helps trace products, improve consumer health and well-being, and increase brand trust. Over the years, widespread food safety incidents have prompted people to focus on food hygiene (Maitiniyazi and Canavari, 2020). People consume daily based on what they think is the correct approach to production, including all steps being performed in a format that aligns with quality, hygiene, and safety regulations (Jin et al., 2023). People's daily food consumption is based on assumptions about a proper strategy, including all stages in full compliance with quality, hygiene, and regulatory safety requirements (Malik et al., 2024a). The data indicate that each year, approximately 600 million people worldwide are impacted by illness caused by the consumption of contaminated food items, and over 40,000 deaths occur for the same reason (Singh and Gandhi, 2015).

As food items pass through borders worldwide, ensuring their safety, quality, and compliance with international standards becomes essential (Khanna et al., 2022). Globalization has increased the requirement for an effective traceability system due to the rising complexity and scope of food supply chains, raising the risk of contamination and fraud. As living standards rise, food safety and quality become more critical (Wang et al., 2021). Despite being the essential food for almost every group, the dairy sector's quality has not improved significantly. In 2023, the worldwide dairy industry reported an estimated value of US$ 944.7 Billion. Imarc group predicts that the market will achieve a value of US$ 1459.3 Billion by 2032, with a compound annual growth rate (CAGR) of 4.95 % between 2024 and 2032 (imarc group, 2024). Factors such as rapid

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urbanization, increasing consumer awareness, technological advancements, demand for dairy-based products, changing consumer preferences, and supportive government policies and regulations drive the market (Hassoun et al., 2024a). The worldwide consumption of dairy products shows its importance among consumers (Chauhan et al., 2020). Therefore, building a reliable Farm to fork food traceability system, especially for dairy products, is essential to ensure safety and quality (Wang et al., 2019). Developing countries need a trusted traceability approach for the dairy industry, where consumers can access information about dairy products (Tan and Ngan, 2020). Traceability, which maintains transparency as an essential factor, ensures access to the required information about the origin of a product along with the processing details (Francisco and Swanson, 2018).

Traceability in the dairy sector is essential due to several crucial aspects. Providing the safety and quality of food is of utmost importance in a global dairy market that is becoming more connected and complicated (Malik et al., 2023). Many researchers have reported cases of adulteration and contamination in the dairy industry globally. Such incidents highlight the need for an effective traceability system (Malik et al., 2024b). In the present scenario, consumers are becoming interested in information about the sources and methods used to produce their food (Casino et al., 2020). In addition, the dairy sector influences the environment due to its utilization of land, consumption of water, and emissions of greenhouse gases. Traceability systems monitor and report these environmental impacts, promoting the adoption of sustainable practices (Hassoun et al., 2024a). Effective traceability enables the optimization of the environmental impact of dairy production, hence contributing to broader sustainability goals. Adhering to globally recognized food safety standards is essential for entering global markets (Tarchi et al., 2024). Traceability solutions enable dairy farmers to comply with these criteria, promoting seamless trade and market access. To summarise, the most recent data emphasizes the increasing size and intricacy of the worldwide dairy industry, emphasizing the necessity for strong and reliable systems to track and trace products (Hassoun et al., 2023). Traceability systems are crucial for the future of the dairy sector as they ensure food safety, build consumer trust, promote sustainability, and facilitate regulatory compliance (Khanna et al., 2022).

Despite its importance, conventional traceability techniques, including manual record management, Radio Frequency Identification (RFID), QR codes, etc., are still being used. Using applications based on IoT, information related to products can be stored in real-time from production to distribution (Casino et al., 2019). Traditional traceability frameworks can be utilized to observe and collect data related to any particular product information in all production and consumption phases. RFID, Near-Field Communication (NFC) technology, Wireless Sensor Network (WSN), etc., can be used for this purpose (Paul et al., 2022). This stored information can provide valuable insights into monitoring food quality. Yet, this complete system depends on the centralized system, so the users rely only on this system to collect and transfer information related to traceability (Feng et al., 2020). Due to the centralized nature of this system, consumers often face many problems, such as collecting details about the transactions and finding out the product's origin (Imeri and Khadraoui, 2018). The fourth industrial revolution highlights the interventions of digital technologies such as artificial intelligence, the Internet of Things (IoT), blockchain, data analytics, etc. that play a key role in traceability advancement. The IoT monitors dairy operations in real-time and is integrated with traceability systems, where AI analyses the data for better management. Similarly, digital technologies like blockchain enable transparency and visibility in the dairy supply chain (Hassoun et al., 2022a).

In the dairy industry, traceability is still a new technology that has yet to reach its full potential. Although traceability methods within the dairy sector have made considerable advancements, there is still an opportunity for potential improvements (Malik et al., 2024b). Current methods for dairy traceability utilize a combination of traditional and digital approaches. Several dairy supply chains rely on manual record-keeping and insufficient digital tools and must be improved to accommodate modern food supply networks' complex and global nature (Hastig and Sodhi, 2020). However, advanced technologies like blockchain and IoT are being progressively adopted. Currently, these technologies are undergoing testing and implementation at various points of the dairy supply chain. While these have demonstrated promise in enhancing the ability to monitor and trace products, there is still a need for further development and integration to achieve general adoption (Hassoun et al., 2022b).

Considering these as research gaps, this study investigates the traceability advancements and their potential for a sustainable dairy future. The authors address the research questions related to the current status of traceability, its potential, and associated challenges. The research objectives include *exploring the current research trends and traceability status in the dairy industry and the potential applications, associated challenges, and future opportunities related to traceability in the dairy industry*.

Considering these research objectives as a beginning point, the authors conducted a systematic review and bibliometric analysis of the existing literature to determine previous research investigating traceability. A descriptive study was conducted to understand the evolution of the research and foresee likely future trends of traceability applications in the dairy field. As there was no detailed evaluation of the traceability in the literature, particularly in the dairy industry, from a strategic viewpoint, it was essential to investigate current research works to make a significant contribution to the scientific literature and highlight the gaps to be studied in subsequent research. The findings from this investigation are intended to serve as a reference point for further research into the application of traceability in various dairy processes and areas and to provide a framework for the successful adoption of the technology in the industry. The assessment enabled the identification of distinct usage patterns based on dairy processing and developing an effective framework for traceability based on the various processes. The remainder of the paper has the following structure: Section 2 discusses the review methodology. Section 3 presents the systematic and bibliometric analysis, Section 4 discusses the findings, and Section 5 concludes the study.

2. Review methodology

A scientific study begins with a literature review (LR), where the researcher understands the terminology, vocabulary, methodologies, regulations, and current trends related to the area of research. The LR significantly contributes to new thinking in the field. It can help future researchers determine the path of action through the research process and provide a deeper understanding and flexibility about the possible options in their study area (Torraco, 2005). LR is defined as a group of references without a well-defined preferential approach based on quantitative measurements and investigation manner. The authors (Tranfield et al., 2003) described the systematic literature review (SLR) as a study that aims to answer specific questions using LR selectively and systematically investigate various aspects, viz. research trends, advancements, challenges, opportunities, etc. (Kitchenham, 2007). An SLR employs a rigorous and reproducible approach to assess and analyze all available research related to a specific topic, subject, or field of research. SLRs generate valuable insights by synthesizing prior research and pinpointing existing gaps (Kamble et al., 2018). For the current review, the authors adopted a three-phased SLR methodology, consisting of a planning phase, searching phase, and review analysis phase, as suggested by (Tranfield et al., 2003).

2.1. *Planning the review*

The review's objective was to explore the concept of traceability, its current status, and its potential applications in the dairy industry. The main focus was understanding traceability and its need in the dairy industry. According to the scope of the review, the following research questions have been formulated:

- *RQ 1. What is the current status of traceability in the dairy industry?*
- *RQ 2. What are the potential applications, associated challenges, and future traceability opportunities in the dairy industry?*

To specify the limits of the review, the authors selected potential keywords covering research questions such as traceability, dairy traceability, sustainability, dairy industry, dairy supply chain, blockchain, transparency, product authentication, consumer trust, food safety, and security to carry out articles search.

2.2. Conducting the review

The review uses an integrated approach to collect and analyze the relevant data. The systematic and bibliometric review approaches were used to evaluate the articles collected from the Web of Science (WoS) database. Compared to other academic databases, including Google Scholar, Wiley, and SCOPUS, WoS is the oldest database for scientific work and the most helpful tool for conducting literature analysis. It has the most extensive citation records (Ellegaard and Wallin, 2015). Also, it consists of the most relevant and impactful journals of high quality (Nishant et al., 2020; Zhao, 2017). A total of 430 articles were searched initially; the authors then applied the inclusion criteria, which included articles published in the English language, full-text articles, articles related to the research theme, and the study included only peer-reviewed articles. The articles published between 2000 and 2023 were chosen. The exclusion criteria include articles published in conference proceedings, editorial notes, etc., articles published in other languages, and articles unrelated to traceability were excluded from the review. After applying these inclusion-exclusion criteria, 269 articles were selected for content analysis. The content analysis highlights 184 irrelevant articles unrelated to the research theme or traceability in dairy, which were excluded. A total of 85 articles were selected for the systematic and bibliometric analysis. Although the process is systematic, there are a few limitations of the methodology, including the fact that the article search was performed on the WoS database only; it may be possible that some articles were not considered for the review. Another area for improvement was the primary language selected for the articles, English; it may be possible that the study excluded potential articles published in other languages.

2.3. Descriptive statistics

The authors performed a descriptive analysis to identify the growth in research related to traceability in the dairy industry. The *biblioshiny* library in R language was used to perform the bibliometric analysis. Table 1 presents the descriptive analysis of articles considered for review. It presents an overview of relevant bibliometric data and statistics about a collection of articles related to traceability in dairy. The scope of analysis includes the timeframe of the publications, sources, authors, keywords, collaboration patterns, etc. Furthermore, it emphasizes the yearly increase in published publications, revealing patterns in the research output as time progresses.

Table 1 presents an overview of the primary information related to the total number of articles collected systematically. Eighty-five articles were collected from 45 sources authored by 374 authors. As the descriptive shows, the review considered articles from 2000 to 2023, and the low collaboration index shows that the research related to traceability is still in the initial phase.

Table 1
Main information and descriptive analysis.

Description	Results
Main Information	
Timespan	2000:2023
Sources (Journals, Books, etc.)	45
Documents	85
Average years from publication	7.26
Average citations per document	22.71
Average citations per year per document	3.455
References	3913
Document Types	
Article	75
Review	10
Document Contents	
Keywords Plus (ID)	340
Author's Keywords (DE)	296
Authors	
Authors	374
Author Appearances	392
Authors of single-authored documents	4
Authors of multi-authored documents	370
Authors Collaboration	
Single-authored documents	4
Documents per Author	0.227
Authors per Document	4.4
Co-Authors per Documents	4.61
Collaboration Index	4.57
Annual Growth Rate	12.74 %

3. Systematic and bibliometric analysis

The research approach includes many aspects of traceability, such as new technologies, rules and regulations, and possible challenges while implementing such technologies into practice. The findings from the bibliometric analysis indicate that research has been done into traceability-related domains in the dairy industry.

Fig. 1 illustrates the current status of the research by indicating the year-wise publication of research articles and shows the annual scientific production with a growth rate of 12.74 % related to traceability in the dairy industry. The growth rate related to the research theme is gaining momentum after 2021, indicating that researchers are interested in traceability and related research areas.

The source impact refers to a source's relevance in any research field. This impact can be evaluated by several parameters, including the number of citations, the number of times researchers have cited a source, the prestige of the source within academics or related industries, and its significance to a particular research field. Fig. 2(a) shows that "The Journal of Cleaner Production" is the most impactful source with a 268 total citation (TC) index, followed by "The Journal of Dairy Science," "Food Chemistry," and "International Dairy Journal". On the other hand, the "most relevant source" commonly relates to a particular publisher that is highly relevant or appropriate to the subject that has been explored. It may not have the most substantial influence on citations or acknowledgment within the field, but it discusses or contributes to the topic under discussion. Evaluating referencing trends to assess which journals are most impactful within such a particular field of research is part of recognizing the most relevant sources. Fig. 2(b) shows the most relevant sources, including the Journal of Dairy Science, British Food Journal, Food Control, Food Chemistry, Food Research International, etc. This can assist in recognizing the implications and relevance of numerous sources in the literature. Such aspects are critical for understanding the framework, developments, and interactions of literature review within a particular research field.

A word cloud is used in bibliometric analysis to illustrate the most relevant keywords in the existing literature and highlight essential and trending research themes. Fig. 3 shows the word cloud and the most relevant words reported in the literature as authors' keywords in parts a and b. Traceability, food safety, blockchain, dairy industry, and sustainability are shown in bigger sizes, indicating researchers' frequent usage of these terms. Part c shows the trends in topics indicated by circles on lines such as traceability-related terms with high frequencies, among others. The occurrence of particular keywords over time is

Fig. 1. Evolution of traceability in dairy (source: authors).

tracked by word growth analysis, which allows researchers to explore the latest developments, transitions in research topics, or the advancement of terms and concepts in a domain. Part d shows such word growth; colored lines indicate different words and growth related to these words over time.

A conceptual structure map analysis can assist in representing the correlation between two themes or concepts in the literature during bibliometric analysis. Fig. 4(a) shows that research related to traceability is correlated with food safety, adulteration, and sustainability in the dairy industry. In Fig. 4(a), dimension 1 presents a transition from traditional methods to advanced technological innovations related to traceability. Dimension 2 highlights a change in general research themes to practical themes such as sustainability, traceability, and food safety. A cluster map indicates the connections among various clusters of related keywords or terms in the relevant literature. It supports the classification of different research topics or fields of study. It categorized the research themes according to relevance and degree of development. Fig. 4(b) shows that researchers focus on several research areas in an integrated manner. The motor theme indicates that the research themes "sustainability" and "blockchain" are influential, highly dense, and well-established from a research point of view. The emerging theme indicates low centrality and less development in research related to these themes. The basic theme presents the main areas that require more research in "the supply chain" and "the dairy industry." Overall, the bibliometric analysis offers a comprehensive view of the evolution of traceability in dairy, focusing on recent trends, the relationship between research themes, and development stages.

3.1. Limitations

The authors list the various limitations of the study, including the use of the WoS database to search for relevant articles on the current research theme. The current study may have overlooked some articles during the selection process due to, for instance, the keywords that were used. Furthermore, because the analysis is based on the authors' interpretation, it depends on how they perceive and categorize the data gathered. The limitation of the bibliometric analysis depends on the articles collected and the data analyzed. The exclusion of any related article may affect the relationship and trends obtained through analysis.

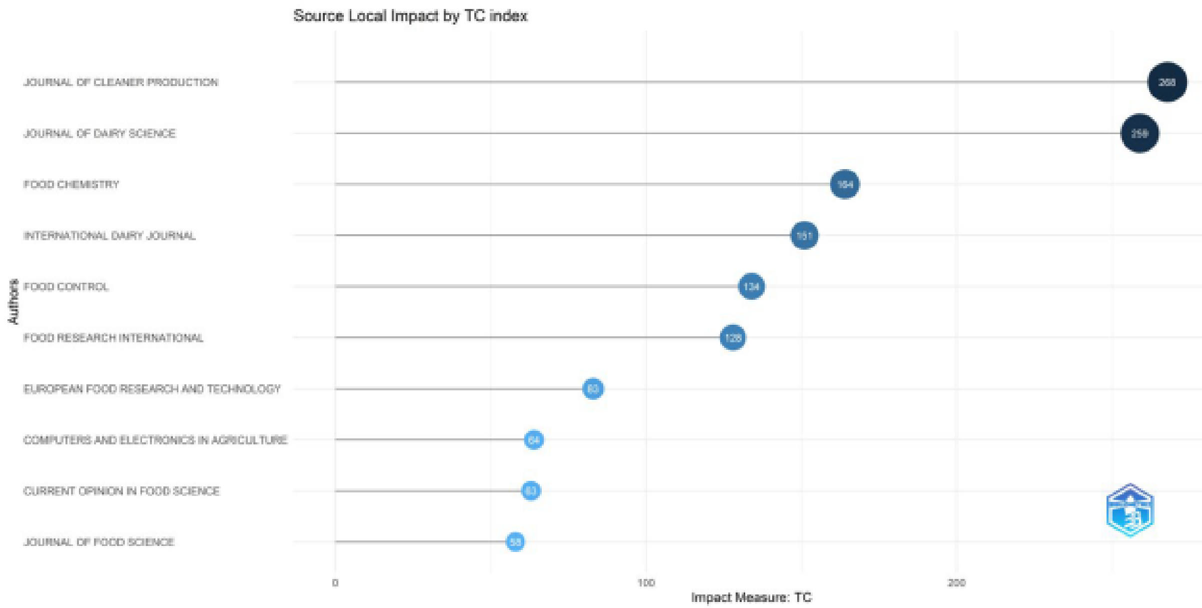
4. Discussions

This section highlights the traceability's past, present, and future. It focuses on the evolution of traceability, existing methods, current status in the dairy industry, potential applications, existing challenges, and future aspects of traceability in the dairy sector.

4.1. Traceability-an overview: past, present, and future

4.1.1. Past: evolution, traditional techniques, and challenges

Traceability in the dairy industry has undergone significant evolution over the years. Traditionally, traceability systems were rudimentary, relying heavily on paper-based records and manual tracking methods (Prashar et al., 2020). These techniques involved recording data at various supply chain stages, such as farm logs, transport records, and batch numbers during processing. While these methods provided a basic level of traceability, they were prone to errors, inefficiencies, and fraud (Casino et al., 2021). The primary challenges included more real-time data, transparency, and difficulty identifying and responding to food safety incidents. Despite these limitations, traditional traceability systems laid the groundwork for more sophisticated approaches by highlighting the need for accurate and comprehensive data tracking throughout the supply chain (Khanna et al., 2022). Traceability systems are expected to trace and track products and their elements through the supply chain. Although traceability must be an end-to-end method, it is achieved in a supply chain of independent firms with their information management. To achieve end-to-end traceability, dairy industry stakeholders must engage in three major events: data acquisition, storage,



(b)

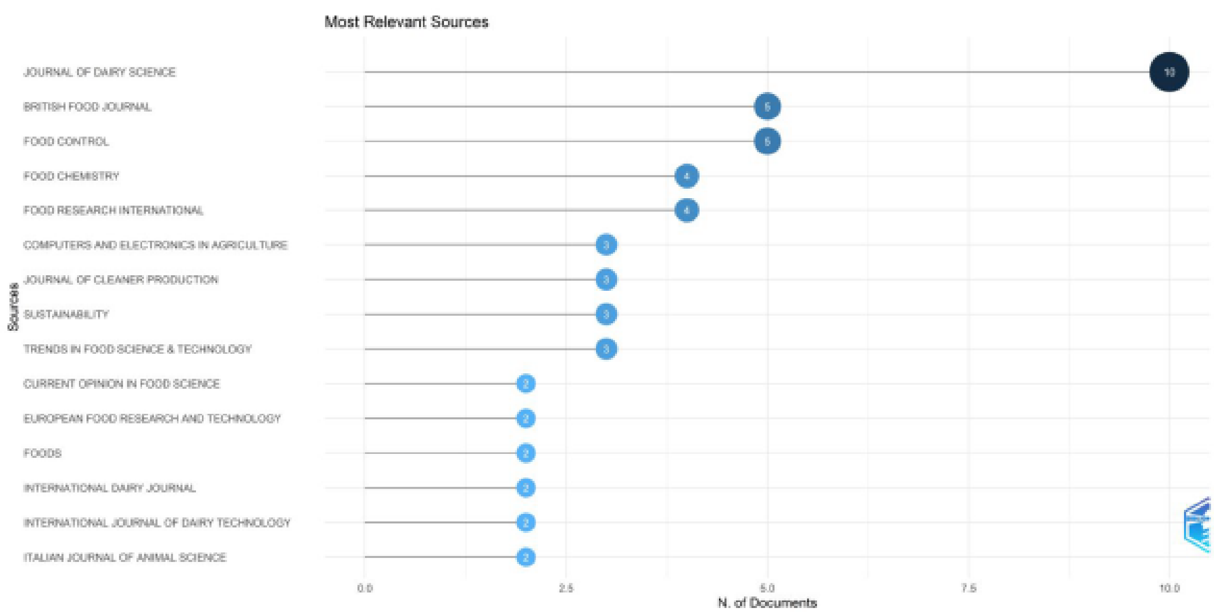


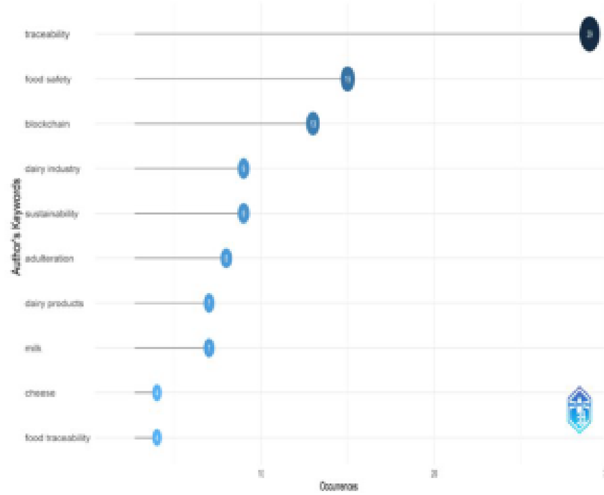
Fig. 2. (a & b): Relevant source analysis (source: authors).

and sharing (Tan and Ngan, 2020). The functionality of the traceability system is mainly dependent on these steps. In data acquisition, all the necessary details related to the product should be captured as described in key data elements (KDE). However, data acquisition can be traditional methods like paper-based or technological ones like QR codes, barcodes, RFID, and IoT sensors (Kumar and Kumar, 2020). Data storage and management of the collected data can be done using a database according to a specified traceability system. The data sharing deals with exchanging this data among all industry stakeholders. For this, an effective traceability system must consist of hardware and software, allowing the system to communicate (Dash et al., 2022).

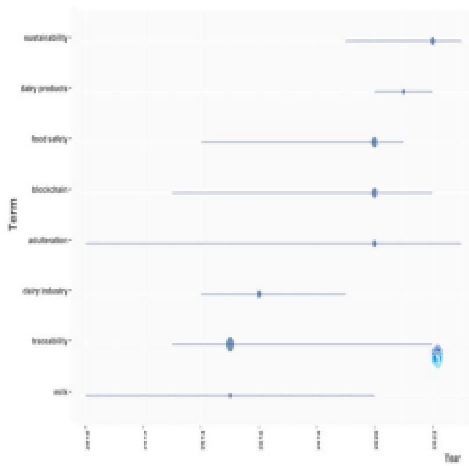
4.1.2. Present: current state of traceability

The dairy industry has embraced advanced technologies to enhance traceability systems in the present scenario. Integrating digital solutions such as blockchain, IoT, and AI has revolutionized traceability, providing real-time, secure, and transparent tracking of dairy products from farm to consumer (Malik et al., 2023). Blockchain technology, for example, offers an immutable ledger that ensures data integrity throughout the supply chain. At the same time, IoT devices enable continuous monitoring of conditions such as temperature and humidity during transportation and storage. These advancements have significantly improved the accuracy and reliability of traceability systems, addressing many of the challenges associated with traditional methods (Hassoun et al., 2024a). However, the current state of traceability has its challenges. The dairy industry faces numerous challenges in implementing digital traceability systems, including high implementation costs, lack of supportive infrastructure, lack of collaboration among stakeholders, lack of awareness, etc. The need for standardization across different systems and concerns about data privacy and security are

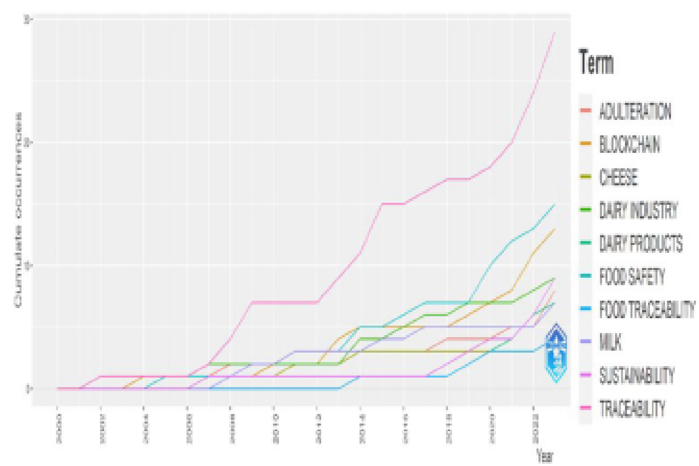
3 (a) : Word Cloud



3 (b) : Most Relevant Words

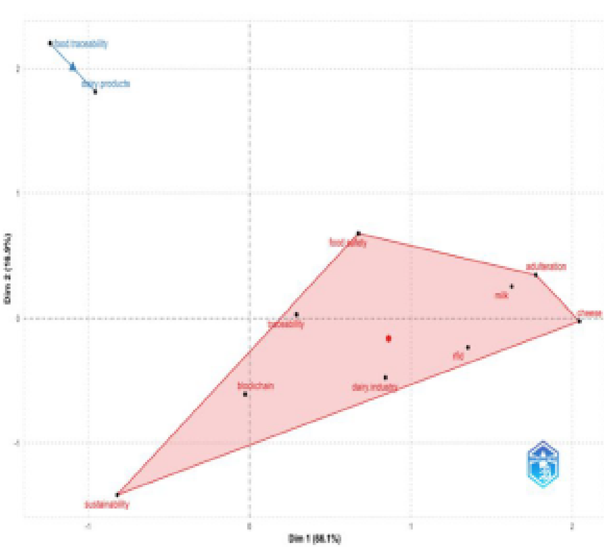


3 (c) : Trend Topics

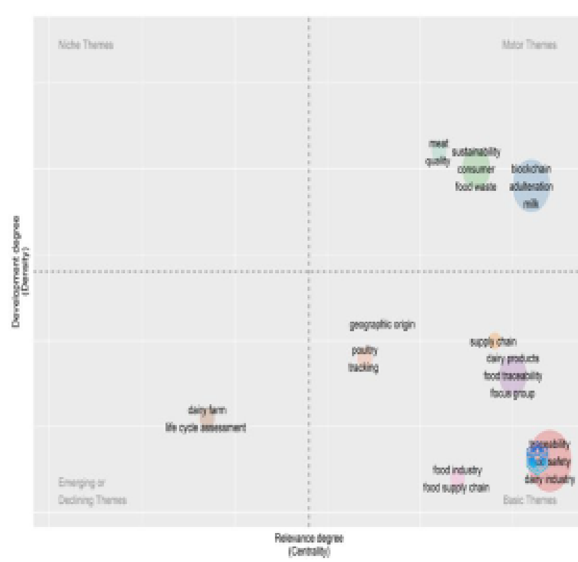


3 (d) : Word Growth

Fig. 3. Research trends related to traceability (source: authors).



4 (a) : Conceptual Structure Map



4 (b) : Cluster Mapping

Fig. 4. Conceptual relationship analysis (source: authors).

ongoing issues that must be addressed to utilize the maximum potential of digital traceability systems (Vern et al., 2023).

Despite the existing challenges, the literature reported successful case studies highlighting the effective integration of digital technologies with traceability systems. These case studies provide important examples of how digital technologies like IoT, AI, and blockchain are being applied to improve traceability systems in the dairy industry (Varavallo et al., 2022). Carrefour Group implemented a blockchain-based traceability system, which allows users to get traceability information by scanning the QR code (Ryan, 2022). Nestle implemented digital solutions to trace milk operations using emerging technologies, AI, and IoT (Usman, 2022). Arla Foods implemented a traceability system to ensure a transparent supply chain using blockchain and QR codes (Best, 2019). Maersk implemented an IoT and blockchain-based traceability system to ensure traceability in logistics for dairy products (Aritua et al., 2021). Many authors have reported the development of traceability systems, including blockchain-based, IoT-based, RFID-based, and QR code-based. Some studies reported integrated traceability systems based on multiple digital technologies like IoT and blockchain. Many authors discussed theoretical concepts for traceability models, adoption and implementation challenges, and the development aspects (Jabbar et al., 2021; Kumar and Kumar, 2020; Wang et al., 2020; Wang et al., 2021). Some authors developed prototype traceability systems that must be implemented in real time to analyze the outcomes and implementation challenges. Despite these advancements in the current scenario, successful practical adoption and implementation of such systems are limited in the dairy industry (Khanna et al., 2022). Practical validation via implementation needs to be improved in the current scenario.

The adoption of traceability is slow in the dairy industry, although other supply chains have utilized traceability to ensure transparency. The researchers highlighted the application of blockchain-based traceability for the meat industry to ensure end-to-end traceability and address issues related to animal welfare (Jo et al., 2022). The researchers developed an integrated traceability system based on RFID and blockchain for the tea industry (Paul et al., 2022). A smart tag-based traceability system was reported for the textile industry to ensure transparency and visibility in the textile supply chain (Aggarwal et al., 2022). These case studies highlight the current developments related to traceability in the dairy industry.

4.1.3. Future: opportunities and challenges

The future of traceability in the dairy industry holds immense potential for further innovation and improvement. Emerging technologies such as advanced data analytics, machine learning, and next-generation IoT devices enable greater insights and control over the supply chain (Malik et al., 2024b). These technologies can enhance predictive analytics, enabling stakeholders to anticipate and mitigate risks before they occur. Developing global standards for traceability systems can also facilitate greater interoperability and collaboration across the industry (Hassoun et al., 2022c). However, the future also presents several challenges. Ensuring the scalability and affordability of advanced traceability solutions for small and medium-sized enterprises remains critical. Moreover, as traceability systems become more complex, there is a need for reliable security measures to protect data from security breaches and unauthorized access (Hassoun et al., 2022d). Addressing these challenges will require concerted efforts from industry stakeholders, policymakers, and technology providers to create a sustainable and resilient traceability infrastructure for the dairy industry. Overall, the evolution of traceability in the dairy industry from traditional paper-based methods to advanced digital solutions highlights the continuous need for innovation to ensure food safety, quality, and sustainability (Hassoun et al., 2024b). By understanding the past, addressing current challenges, and leveraging future opportunities, the dairy industry can achieve a comprehensive and effective traceability system that benefits all stakeholders.

4.2. Traceability in dairy advancements

The authors analyze the literature to investigate the dairy industry's status in terms of technological advancements. The selected articles are categorized into four aspects: dairy management, consumer, sustainability indicators, and regulatory aspects. Further content analysis divided dairy management aspects into animal welfare aspects, farmer aspects, technological advancements, supply chain management, and operational efficiency; consumer aspects into food safety and security, food quality, and awareness; sustainability indicators into economic, social, and environmental aspects; and finally regulatory aspects regulations and compliances. All 85 articles were analyzed and divided into these categories and subcategories to investigate the current status of research related to every aspect. The section-wise overview of every aspect and related research is presented as supplementary material in Table A1.

The evaluation of Table A1 indicates that 27 % of researchers focused on animal aspects, 16 % on farmers aspects, 44 % on technological advancements, 31 % on supply chain management, 14 % on operational efficiency, 52 % on food safety and security aspects, 34 % on food quality aspects, 22 % on awareness among stakeholders, 22 % on economic elements, 38 % on social and environmental aspects in sustainability indicators, and only 9 % on regulation and compliance aspects in the dairy industry. Only a small number of studies examined the integrated elements of dairy. These findings indicate a significant requirement for implementing the integrated dairy management concept. This concept can improve research in crucial areas such as quality, safety, awareness, welfare, and transparency, ensuring a sustainable future for the dairy industry (Malik et al., 2023).

Despite these technological advancements, the dairy industry still faces several challenges. The authors identify the challenges associated with the dairy industry through content analysis. Table 2 presents identified challenges, which are categorized area-wise.

Table 2 highlights the challenges that can be addressed by implementing an effective traceability system in the dairy industry.

4.3. Potential applications of traceability in dairy

This section discusses the potential applications of traceability within the dairy industry. Traceability systems help the industry determine the source and intensity of security or elevated tracking concerns. It reduces the time and utilization of unreliable products, which minimizes the chances for negative impressions, risks, and criticism (Mor et al., 2021). Effectively implementing a traceability system will enable the industry to deal with product recalls, maintenance, and quality control issues. From such a single piece of information, the processor can trace a defective product back to its origin and determine whether other objects in the same batch are defective (Feil et al., 2023). Many consumers, including restaurants, hotels, and a few shopping malls, are now guiding their vendors to establish traceability systems and regularly ensure that the system works. Fig. 5 shows some potential applications of traceability in the dairy industry. Product authenticity, quality control, enhanced product recall, token incentive system, etc., are possible outcomes of traceability implementation (Malik et al., 2023).

As shown in the figure above, an effective traceable system can enhance the dairy industry in various ways, such as product traceability and quality control, which includes all quality parameters throughout the complete processing phase to ensure that consumers receive quality milk products. After that, it will ease product recall in case of contaminated and adulterated products are delivered. Smart contracts can tackle these issues via real-time audibility (Bottoni et al., 2020). No doubt, it will also increase brand value for any industry. It will improve supply chain performance by eliminating the effort and time required to manage inventories, balance transactions, product collections, and bills. It will simplify contract management with vendors, suppliers, and retailers. Complete process will make all processes transparent (Cabrera

Table 2
Potential traceability enablers in the dairy industry.

Dairy Segment	Challenges	Potential Application/ solution through Traceability	References
Production	• Balancing milk production with costs • Sustainable farming practices • Accessing quality feed consistently • Animal welfare issues • Lack of real-time monitoring • Unfair milk pricing	• Implementing IoT sensors for monitoring animal health and nutrition • Using data analytics for optimized feed and resource management • Traceability systems for feed sourcing and farm practices	(Cabrera and Fadul-Pacheco, 2021; Lovarelli et al., 2020)
Collection	• Ensuring milk quality during transport • Managing variations in milk composition • Adulteration issues • Milking Hygiene • Data Management • Transparency	• RFID tags for milk containers to track quality and origin • Digital platforms for real-time data on milk quality and quantity	(Wahyono et al., 2023; Schillings et al., 2023)
Transportation	• Maintaining cold chain integrity • Addressing logistical challenges • Real-time temperature monitoring	• IoT devices for monitoring temperature during transit • GPS tracking for efficient route planning and management	(Hassoun et al., 2023; Malik et al., 2023)
Processing	• Compliance with quality and safety standards • Efficient processing of varying milk volumes • Sanitary and hygiene problems • Vulnerability to adulteration and contamination • Implementation of regulatory requirements • Wastage problem • Nutrient Degradation • Improper traceability system	• Blockchain for transparent supply chain and quality control • Automated systems for quality assurance and processing	(Lopes et al., 2020; Varavallo et al., 2022)
Distribution	• Maintaining product quality during distribution • Optimizing delivery routes • Improper traceability system	• Digital inventory management for product tracking • Route optimization using AI algorithms	(Freeman et al., 2022; Mangla et al., 2019)
Dairy Management	• Balancing profitability with sustainability • Adapting to technological advancements • Incompatible infrastructure • Improper data management	• Integrated management software for farm operations • AI-based predictive models for resource optimization	(Hassoun et al., 2024a, 2023; Malik et al., 2024b, 2023)
Environmental Challenges	• Managing waste • Reducing carbon footprint	• Data-driven waste management systems • IoT sensors for environmental impact monitoring	(Hassoun et al., 2024b; Tarchi et al., 2024)
Regulations	• Ensuring compliance with regulations	• Digital record-keeping for regulatory compliance • Blockchain for transparent audits and compliance checks	(Freeman et al., 2022; Khanna et al., 2022; Vern et al., 2023)

and Fadul-Pacheco, 2021).

Implementation of traceability in the dairy industry can optimize the sector in terms of operational efficiency, market access, and risk mitigation. Some potential operational benefits are inventory level accuracy to tackle the demands, improving tracking to minimize errors, and lowering costs and waste (Hassoun et al., 2024b). Improving all these factors can also enhance the brand value of the industry by creating a transparent system that will attract more customers and expand the market scale. It can also reduce product recalls and customer issues related to information sharing (Khanna et al., 2022). Implementing product traceability can benefit all stakeholders in the dairy industry as farmers will get direct benefits as per the quality of their product, the industry will be able to establish a direct relationship with all stakeholders, consumers will get safe and secure food, and it will also tackle issues like cost reduction, minimum wastage, etc. (Hastig and Sodhi, 2020).

4.4. *Traceability and sustainability goals*

In the dairy industry, traceability systems allow for the real-time monitoring of materials utilized at every production stage. This includes keeping track of feed intake, water consumption, energy intake, and waste production (Yadav and Singh, 2020). By analyzing this data, food producers can detect systemic problems and take adequate measures to optimize resource utilization, promoting sustainable development (Olsen and Borit, 2018). An effective traceability system contributes to waste reduction throughout the supply chain. It enables supply chain management, as well as the reduction of excess supply and reduced wastage. Dairy stakeholders can significantly minimize landfill burden and resource conservation by identifying the causes of waste and deficiencies (Astill et al., 2019). Traceability systems help to conserve the environment by allowing the recognition of sustainability solutions. This involves following the path of environment-conscious farming techniques such as organic or eco-friendly agriculture. It also makes it easier to track the environmental effects of dairy farming, inspiring the implementation of practices that reduce adverse impacts (Lovarelli et al., 2020).

Effective traceability systems optimize dairy operations, saving money. These systems improve inventory management, logistics, and operational efficiency. Traceability reduces waste and improves efficiency and market access, helping dairy operations stay profitable. Customers frequently want transparency and accountability in food

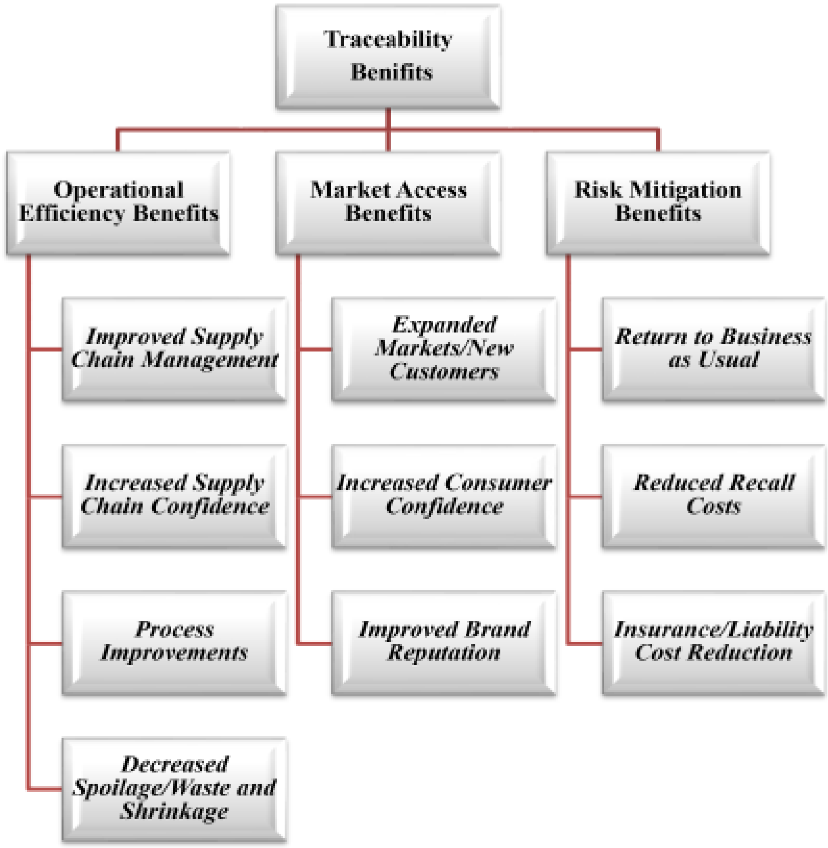


Fig. 5. Potential traceability applications in the dairy industry (source: authors).

production (Duruz et al., 2020). Traceability ensures product quality, ethical sourcing, and environmental compliance, boosting market competitiveness. It enables customers to track dairy product origin and production, promoting ethical sourcing. Transparency builds customer trust and loyalty for ethical and sustainable brands (Michie et al., 2020). Traceability indirectly builds communities by promoting sustainable farming. Fairtrade and sustainable agriculture improve dairy farmers' livelihoods and local communities. Sustainability and dairy traceability are intertwined. Transparency, accountability, and responsible dairy supply chain practices promote environmental preservation, economic productivity, and social responsibility. These interconnected factors help achieve sustainability in the dairy industry (Mangla et al., 2019). Fig. 6 shows that adopting digital and decentralized traceability in the dairy sector can considerably contribute to many UN SDGs.

Digital technologies integrated with a traceability system can significantly enhance food quality and safety, minimize food spoilage, and transparency in the dairy supply chain. It helps ensure everyone's access to safe, healthy, and adequate food, aligning with SDG 2 (Hassoun et al., 2022e). Implementing digital traceability systems can improve food safety measures by lowering the risk of contamination and disease spread via dairy products. It contributes to SDG 3 by boosting consumer health and well-being (Malik et al., 2023). By verifying the safety and quality of dairy products delivered to cities, digital traceability can help in metropolitan settings. It creates sustainable and resilient cities by providing safe and dependable food sources. Digital traceability encourages responsible consumption by informing consumers about dairy products' origin, manufacturing methods, and environmental impact. It promotes the dairy sector's sustainable production techniques (Khanna et al., 2022). Implementing digital technologies for traceability in the dairy business can lead to more efficient resource management, decreased waste, and reduced environmental impact. It contributes to efforts to prevent climate change, corresponding with SDG 13 (Malik et al., 2023). Although SGD 15 mainly focuses on the land-related ecosystem, dairy traceability indirectly supports this SDG as it ensures minimal environmental impacts and conserves resources in dairy. Collaboration among dairy sector stakeholders to adopt digital traceability systems builds partnerships for long-term development. It promotes information sharing, technology innovation, and capacity-building activities to accomplish several SDGs (Jouzdani and Govindan, 2021). In the dairy industry, traceability enhances operating effectiveness and corresponds with the globalized production, health, and sustainability goals. It significantly improves real-time monitoring, effective decisions, and transparency along the dairy supply chain, contributing to numerous UN SDGs.

4.5. *Opportunities and future scopes*

4.5.1. *Emerging opportunities in the developing countries*

Innovative technology such as AI, IoT, and blockchain has supported in reducing milk waste, digitizing operational processes, improving milk production, developing last-mile logistics infrastructure, monitoring cattle health, detecting anomalies in milk production, and forecasting weather patterns (Kramer and Bovenkerk, 2024). Technology usage in the dairy sector has evolved from evaluating milk composition or automated milk collecting in villages to milk airlifting, mechanical dairy plant operations, and assessing total milk quality indicators. Furthermore, technological adoption has resulted in novel solutions such as sensors identifying whether the cow is ready for milking, robotic milking equipment, blockchain for product traceability, livestock monitoring, and drones (Nagar et al., 2021). Integrated technological solutions can be implemented in dairy to address critical issues such as milk adulteration, quality, data management, and real-time monitoring sustainably, which can be a game-changer strategy, especially for developing countries (Malik et al., 2023). Traceability can be that component in the

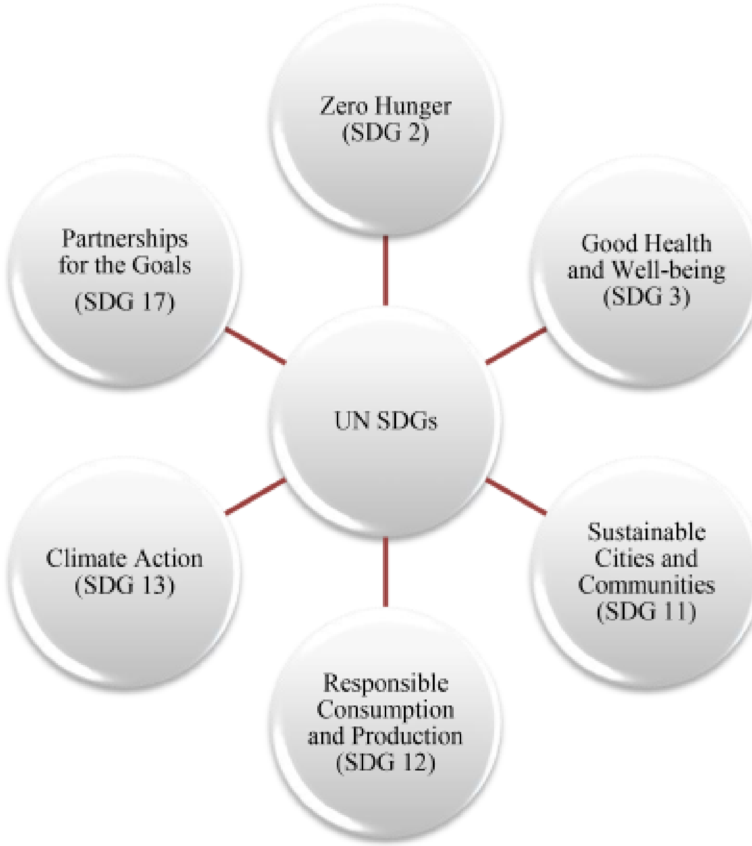


Fig. 6. Traceability and UN SDGs (source: authors).

supply chain that can transparently transform the operations. Literature reported adopting advanced digital traceability systems, especially in developed countries. There are tremendous opportunities for developing countries to adopt and implement such traceability systems to enhance their supply chain operation and establish themselves as potential competitors in global dairy (Hassoun et al., 2022c).

4.5.2. Future scopes

This section discusses the future opportunities to improve traceability evolution and adoption of traceability. Stakeholder collaboration, technological advances, and regulation strengthening are needed to improve traceability practices in the dairy industry. Investment in developing cost-effective, user-friendly, and sustainable traceability solutions is essential. Consumer awareness about the importance of traceable dairy products and creating demand for them can enhance traceability implementation in the dairy industry. Adopting these technological advancements keeps the environment and ethical practices on priority and promotes dairy traceability. The research findings show a need for an integrated and decentralized traceability system in the dairy industry. Digital technologies such as blockchain, IoT, AI, and data analytics can potentially enhance the dairy's operational activities. Immutable and decentralized characteristics of blockchain technology can ensure a transparent traceability system in the dairy industry. Proper integration of IoT with traceability systems can monitor activities in real-time, enhance operational efficiencies, and minimize waste issues in the dairy industry. AI-enabled data analytics can improve inventory and supply chain management to promote sustainability. Future research should focus on the complete dairy integration concept, which can integrate traceability systems with sustainability indicators such as carbon emission, circular economy practices, and social aspects. Implementing such a system will allow dairy stakeholders to monitor and improve the environmental and economic activities throughout the supply chain. Integrated traceability concepts will pave the way for a sustainable roadmap for the dairy industry.

4.6. Implications of the research

The study offers significant implications for dairy stakeholders, consumers, researchers, and regulators. The results highlight the need for effective traceability systems to enhance productivity, safety, and quality. The study pointed out several aspects that indicate the need for an effective traceability system in the dairy industry. The dairy stakeholder can utilize the findings to adopt and implement a traceability system integrated with digital technologies to optimize their supply chain operations. The research highlights the critical role of advanced traceability systems in the dairy sector, which provide advantages to producers by enhancing operational efficiency and compliance and to consumers by ensuring enhanced security and transparency.

The study highlights traceability needs, importance, and applications from a consumer perspective. Effective traceability systems have the potential to benefit consumers significantly. The study pointed out that responsible consumer requirements and preferences towards the demand for traceable dairy products can motivate producers to implement traceability systems.

The research findings offer implications for policymakers. The findings pointed out the root challenges affecting traceability implementation and uncovered several aspects highlighting the need for an effective traceability system for the dairy industry. Policymakers can utilize these findings and develop efficient technological adoption and traceability implementation policies by supporting industry stakeholders. The incentive schemes, subsidies, and user-friendly producers can enhance traceability implementation.

The research offers future opportunities related to traceability advancements and implementation in supply chains. The findings pointed out deficiencies in the current body of literature and focused on the requirement of an additional investigation into the integration of digital technologies with traceability methods. These findings can serve as the starting point for researchers to investigate challenges such as cost, interoperability, scalability, and development. Additionally, researchers can explore the industrial requirements related to traceability implementations. Developing a readiness index for dairy and consumer and industrial perceptions towards adopting traceability can be investigated to promote the research. The inclusion of Industry 5.0 can be explored in future research.

5. Conclusion

The current state of research on traceability and its applications in the dairy industry was investigated in this study using a systematic literature review and bibliometric analysis. The bibliometric analysis highlighted the trends, research themes, and keyword analysis, showing the research growth in a traceability context. The findings indicate a noticeable growth in research related to traceability in the dairy. Further, the content analysis shows that research related to traceability in many aspects of the dairy industry still needs to be completed. Digital traceability is still in its infancy stage in the dairy context. The study pointed out the challenges faced by the dairy sector, including issues related to adulteration, milk safety, quality, transparency in the supply chain, lack of infrastructure, and awareness. The analysis indicates an immense need for an effective traceability system for the dairy industry.

This research identified old traditional techniques such as RFID, QR codes, barcodes, and paper-based systems used in many supply chains, including dairy. However, the centralized nature of these solutions makes them more vulnerable to data tampering and less efficient in terms of transparency. It is also observed that government support for traceability regulations and standards needs to be increased. Instead, the government should promote traceability implementation in the dairy industry to make the process transparent. The findings highlighted the evolution of traceability with the integration of digital technologies. More literature is needed to support traceability implementation in the dairy industry. Overall, the study highlighted the past, present, and future of traceability.

Future studies can explore the factors that affect an effective traceability system in the dairy industry. A traceability system based on decentralized data collection technology, such as blockchain, can be very effective in the dairy industry. The implementation challenges related to traceability systems based on the blockchain can be explored further from an industrial/stakeholder perspective. Industry stakeholders can utilize the findings to streamline their traceability initiatives; regulators can make effective policies to support the adoption and implementation of advanced traceability systems, and researchers can utilize the findings to develop cost-effective and more robust traceability systems for dairy. Global regulatory bodies can utilize the research findings to ensure the implementation of robust and reliable traceability systems worldwide.

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Ethical statement – studies in humans and animals

Authors declare that the research conducted complied with the ethical standards in accordance with Helsinki Declaration.

CRediT authorship contribution statement

Mohit Malik: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vijay Kumar Gahlawat:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization. **Rahul S Mor:** Writing – review & editing, Visualization, Validation, Supervision, Methodology. **Manish Kumar Singh:** Writing – original draft, Investigation, Formal analysis.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

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Supplementary materials

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