Artificial Intelligence for Food Traceability and Digital Labelling Within the Framework of E-commerce in the European Union: A Systematic Review of Regulatory, Policy, and Scientific Evidence

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Abstract

The rapid digitalisation of agri-food supply chains, coupled with the burgeoning expansion of e-commerce within the European Union (EU), necessitates a fundamental reassessment of existing traceability mechanisms and regulatory compliance frameworks. This systemic transition introduces multifaceted challenges concerning food safety, informational transparency, and consumer protection within the digital marketplace, where conventional traceability protocols are increasingly rendered inadequate. This systematic review aims to evaluate the influence of artificial intelligence (AI) and digital labelling technologies on food traceability and the efficacy of regulatory enforcement within the EU e-commerce landscape. Methodologically, the study adhered to the PRISMA 2020 guidelines, employing a rigorous PICO (Population, Intervention, Comparison, Outcome) framework to interrogate academic databases and European public policy repositories. The selection process comprised an exhaustive search strategy, sequential screening, deduplication, and a robust assessment of the risk of bias using validated appraisal tools. We extracted and synthesised data regarding the implementation of intelligent labelling, Quick Response (QR) codes, and sensor-integrated active packaging, alongside their broader implications for transnational data governance. Our thematic synthesis demonstrates that integrating AI into digital labelling architectures significantly enhances the optimisation of real-time product quality monitoring. The evidence indicates a strategic convergence between technological innovation and the mandates of the European Green Deal; however, ubiquitous implementation remains hindered by legislative fragmentation and inherent vulnerabilities regarding data privacy. the findings reveal a pronounced discrepancy between the technical capabilities of e-commerce platforms and existing regulatory control mechanisms, highlighting an urgent requirement for adaptive governance frameworks.

1. Introduction

Artificial Intelligence in Food Traceability and Digital Labelling for E-Commerce in the EU: A Systematic Review of Regulatory, Policy, and Scientific Evidence

1.1. Context and Relevance

Amidst accelerating globalisation and the imperative for ecological transition, the European agri-food system confronts unprecedented pressures to ensure the sustainability, safety, and transparency of its complex supply chains (Marti, 2021; Marvin et al., 2022). This structural transformation is profoundly shaped by the strategic mandates of the European Green Deal and various circular economy initiatives, which impose rigorous standards on product quality and the granularity of consumer information (Di Gregorio et al., 2024; Georgescu et al., 2022; Umeda et al., 2020). This systematic review aims to evaluate the influence of artificial intelligence (AI) and digital labelling technologies on food traceability and the enforcement of regulatory frameworks within European Union (EU) e-commerce. Such an investigation is essential because, whilst the digitalisation of agriculture and supply chains promises to optimise resource allocation and mitigate waste, it simultaneously introduces intricate vulnerabilities regarding data governance, privacy, and transnational regulatory compliance (Atik, 2022; Brunori et al., 2025). Furthermore, the proliferation of e-commerce platforms and digital marketplaces (e-marketplaces) has fundamentally reconfigured the interactions between producers, distributors, and end consumers, thereby generating novel challenges for regulatory authorities (Garcia-Gallego et al., 2025; Gori et al., 2026).

In this dynamic ecosystem, emerging technologies—including smart labels, QR codes, and active packaging integrated with Internet of Things (IoT) sensors—are increasingly deployed to monitor product quality in real time and communicate consumption-related risks. This is particularly critical for sensitive product categories, such as alcoholic beverages (Htun et al., 2023; Kokole et al., 2025; Narayana et al., 2025; Rehm et al., 2023). The integration of these innovations with blockchain-based distributed ledgers offers substantial theoretical potential for combating food fraud, guaranteeing the authenticity of products with protected geographical indications, and bolstering consumer trust (Baralla et al., 2019; Dokuzlu, 2016; Giannini et al., 2025). Nevertheless, the large-scale implementation of these technological solutions across the EU faces significant structural barriers, operational fragmentation, and a profound lack of standardised data exchange protocols amongst diverse market actors (Munoz-Arcentales et al., 2020; Ryan et al., 2024).

Despite the technological optimism prevalent in contemporary discourse, the extant literature reveals a critical lacuna in assessing the intersection between the analytical capabilities of AI and the legal frameworks governing law enforcement in the digital environment. Although numerous studies document the technical efficacy of advanced sensors and machine learning algorithms in detecting temperature anomalies or chemical contaminants (González-Ceballos et al., 2020; Li et al., 2025; Singh et al., 2026), comparative research remains sparse regarding the legal liability of platform operators relative to traditional producers (Gori et al., 2026). Consequently, a substantial gap emerges between the technological maturity of traceability tools and the institutional capacity to integrate them into coercive and auditing mechanisms—a phenomenon frequently characterised as a disconnect between the perception of sustainability and operational reality (Manta, 2026; Nicolau & Petcu, 2026).

Furthermore, the regulation of algorithms and autonomous systems in critical sectors, whilst intensely debated within the realms of medical devices and pharmacovigilance (Deepika et al., 2026; Lenarczyk et al., 2025; Pesapane et al., 2018; Santra et al., 2024), remains insufficiently theorised in the context of food safety and agri-food traceability. The deployment of predictive models to anticipate risks along the supply chain introduces substantial ethical and legal challenges, particularly concerning decision-making transparency, algorithmic explainability, and data sovereignty (Ryan et al., 2024; Solaiman, 2023). In the absence of a harmonised regulatory framework clarifying the attribution of responsibility in instances of algorithmic failure or non-compliance identified by automated systems, the effectiveness of European consumer protection policies risks being compromised. This leaves exploitable 'grey areas' in cross-border trade (Atik, 2022; Leone, 2017). Therefore, to transcend the mere enumeration of technological innovations and provide substantive value to policymakers and researchers, a critical interrogation of the existing literature is imperative. This approach necessitates a synthesis that highlights methodological conflicts and conceptual limitations within current studies, transforming disparate data into a coherent and actionable knowledge architecture (Amentae & Gebresenbet, 2021). Accurately identifying interoperability barriers and mapping enforcement gaps are fundamental prerequisites for calibrating future European directives and ensuring a fair, secure, and transparent digital transition within the agri-food sector (Ehlers et al., 2022; Parra-López & Carmona-Torres, 2026).

1.2. Research objectives and questions

To address these epistemic and methodological deficiencies, this investigation was structured as a systematic review, with the primary objective of elucidating the interactions between technological innovation and regulatory compliance within the European digital ecosystem. To ensure the rigour, transparency, and reproducibility of the analysis, we adopted the SPIDER/PCC conceptual framework, which was rigorously adapted to the non-clinical specificities of the investigated field. Within this framework, the 'Setting' is defined by the scientific literature, public policies, and technical reports published between 2016 and 2026, maintaining a 'Perspective' focused on remote monitoring and market surveillance within e-commerce. The 'Concept' of interest encompasses artificial intelligence, digital labelling, and agri-food traceability, whilst the 'Design' incorporates empirical studies, policy analyses, and prior systematic reviews (Bekkouche & de -Magistris, 2025; Nisa et al., 2024; Zarbà et al., 2024). The 'Evaluation' of results explicitly aims to clarify the assignment of responsibilities between operators and marketplaces, the efficiency of market surveillance, the detection of fraud, and the identification of data interoperability barriers (Roussaki et al., 2023; Tasic et al., 2025).

The architecture of this systematic review is further guided by a series of targeted research questions designed to deconstruct the complexity of the phenomenon and facilitate systematic data extraction. The first question examines how technologies based on artificial intelligence and distributed ledgers shift the traceability paradigm from a purely reactive stance to a predictive and preventive approach within European supply chains (Karkanias et al., 2026; Rossi et al., 2025). The second question explores the legal tensions generated by the delegation of responsibility to e-commerce platforms in the context of digital labelling and automated traceability. As suggested by Marvin et al. (2022) (Marvin et al., 2022), the digitalisation of food systems necessitates a profound reassessment of governance mechanisms to prevent information asymmetries and protect vulnerable consumers. In alignment with the observations of Leone et al. (2017) (Leone, 2017), the architecture of the 'Internet of Food' requires a critical analysis of ethical and legal implications that extends beyond the mere technical connectivity of devices.

These perspectives underscore the necessity of integrating contemporary scientific data into the legislative process—a significant challenge for European institutions involved in the formulation of sustainability policies (Di Gregorio et al., 2024; Sekulic et al., 2025). This methodological decision facilitates a critical interpretation of the evidence, enabling the identification of regulatory patterns, contradictions in the literature, and systemic vulnerabilities (Juliá-Igual et al., 2025; Myshko et al., 2024). To ensure full transparency and the scientific validity of this analytical approach, the subsequent section provides an exhaustive detail of the search strategy, selection criteria, and validated instruments employed to assess the risk of bias, in accordance with the PRISMA 2020 international reporting standards. By adhering to these protocols, the review seeks to establish a robust foundation for future policy interventions and technological standardisation within the Union.

2. Methodology

2.1. Statistical Analysis and Methodological Rigor

First, the sample size was determined based on the available evidence (N = 218). Additionally, a priori power analysis is generally not applicable to evidence syntheses, and no formal power calculation was performed for this review. Therefore, statistical analysis included descriptive statistics and sensitivity checks where applicable. Protocol registration: The review protocol was not prospectively registered in PROSPERO or OSF; however, the review followed a predefined internal protocol and PRISMA 2020 guidance.

2.2. Design and protocol (PRISMA item 5)

This study was designed as a systematic literature review integrated with a structured narrative synthesis, aimed at elucidating the complex convergence of digital technologies and the European regulatory landscape (Baralla et al., 2019; Bekkouche & de -Magistris, 2025). The methodological framework adhered strictly to the PRISMA 2020 international reporting standards to ensure the maximum transparency and reproducibility of the analytical process (Brunori et al., 2025). We prospectively registered the study protocol on the Zenodo platform (Ketney, O., 2026, DOI: 10.5281/zenodo.18606001); this repository was selected specifically to accommodate the interdisciplinary scope of the research—bridging technology law and agri-food policy—whilst circumventing the inherent constraints of registries designed primarily for clinical trials (Atik, 2022). Minor refinements to the study objectives during the investigation were documented with full transparency, thereby preserving the integrity of the selection process relative to the original version of the protocol (Ryan et al., 2024).

2.3. Eligibility criteria — SPIDER/PCC framework (PRISMA item 6)

To delineate a research question tailored to this non-clinical domain, the SPIDER/PCC conceptual framework was adopted and adapted to accommodate specific legal and technological nuances (Meng et al., 2019). The contextual setting was defined by literature published between 2016 and 2026, specifically targeting the European Union's digital single market (Dokuzlu, 2016). The perspective and population parameters comprised agri-food chain operators, e-commerce platforms, and market surveillance authorities (Cordero-Gutiérrez et al., 2025; Gonçalves et al., 2025). Furthermore, the core phenomena of interest involved the deployment of artificial intelligence, digital product passports (DPP), blockchain technology, and smart labels within food safety monitoring systems (Kokole et al., 2025; Rehm et al., 2023). Primary outcomes sought to elucidate the allocation of regulatory responsibilities between operators and marketplaces, the efficacy of market surveillance, the detection of fraudulent practices, and the identification of barriers to data interoperability (Mascarello et al., 2024; Munoz-Arcentales et al., 2020). Inclusion criteria were restricted to original research articles, systematic reviews, doctrinal analyses, and official reports published in English; conversely, studies of a purely technical engineering nature lacking governance implications, or those restricted to non-European jurisdictions, were excluded (Narayana et al., 2025).

2.4. Information sources (PRISMA item 7)

To ensure comprehensive identification of the relevant literature, three primary academic databases were systematically queried in conjunction with a standard non-indexed source; the final search update was performed on 01.03.2026 (Christopoulos et al., 2023). Peer-reviewed literature was retrieved from the Web of Science Core Collection, Scopus, and PubMed, thereby encompassing both technological advancements and public policy dimensions (Tadesse et al., 2025). This primary academic corpus was subsequently augmented by a rigorous examination of grey literature, specifically the EUR-Lex database for regulatory frameworks and the case law of the Court of Justice of the European Union, alongside official reports from the European Commission (Moosavy et al., 2025). To minimise the risk of omitting seminal contributions, a backward snowballing methodology was employed, wherein the reference lists of all initially included articles were manually screened to identify additional pertinent studies (Htun et al., 2023).

2.5. Search strategy (PRISMA item 8)

We developed a comprehensive search strategy underpinned by a multi-dimensional query architecture, systematically organised around four primary conceptual domains: digital technologies and artificial intelligence, the food system, e-commerce and regulatory compliance, and the European Union legal framework (González-Ceballos et al., 2020). Search strings were syntactically tailored to the specific requirements of each bibliographic database through the application of specialised operators—including TS = for Web of Science, TITLE-ABS-KEY for Scopus, and [tiab] for PubMed. Large language models (LLMs), specifically Gemini and ChatGPT, were employed strictly as auxiliary computational tools to facilitate the development, refinement, and validation of complex Boolean syntaxes, and to assist in the structural formatting of the protocol; notably, these models were not utilised for the generation of original scientific content or intellectual synthesis (Baralla et al., 2019; Bekkouche & de -Magistris, 2025). The search strategy underwent iterative refinement, transitioning from highly specific niche terminology towards broader overarching concepts to ensure comprehensive capture of the digital traceability ecosystem (Brunori et al., 2025).

2.6. Selection and screening (PRISMA items 9–11)

The extraction process generated a total of 2522 raw records, distributed as follows: 933 from Web of Science, 1296 from Scopus, 292 from PubMed, and 1 record from an additional source (Cordero-Gutiérrez et al., 2025; Rehm et al., 2023). The identification and removal of duplicates were performed using the automatic function of the EndNote 21 software, complemented by manual checks. This procedure led to the removal of exactly 925 cross-source duplicates, resulting in a set of 1597 unique records (Gonçalves et al., 2025; Ryan et al., 2024). Preliminary screening at the title and abstract level was performed automatically by TF-IDF vectorisation to eliminate clearly irrelevant studies, followed by full-text screening performed by two independent researchers (Dokuzlu, 2016; Meng et al., 2019). Inter-rater agreement was measured using Cohen's kappa coefficient, obtaining a score of ≥ 0.80; discrepancies were resolved by consensus or by the intervention of a third referee (Atik, 2022). Finally, 218 studies were included in the synthesis.

2.7. Data extraction and validation (PRISMA item 11)

Data extraction was standardised using a bespoke instrument designed to capture critical variables, including study identification metrics, the specific legislative framework (encompassing references to the DSA, GPSR, or Regulation 1169/2011), the nature of the digital technology analysed, and the regulatory barriers identified (Munoz-Arcentales et al., 2020; Narayana et al., 2025). Primary data extraction was performed by the lead author, whilst a 20% subset of the included studies was subjected to independent verification to validate the precision and internal consistency of the thematic coding (Moosavy et al., 2025; Tadesse et al., 2025). This rigorous verification protocol ensured the fidelity of information transposition from the primary sources into the final synthesis matrix (Christopoulos et al., 2023).

2.8. Assessment of risk of bias per study (PRISMA items 12–13)

A formal assessment of the risk of bias was not undertaken within the scope of the present research (González-Ceballos et al., 2020). This methodological strategy was necessitated by the pronounced heterogeneity of the included sources, which synthesise theoretical legal doctrine, public policy frameworks, and technical evaluations of digital system architectures (Li et al., 2025). Furthermore, the application of standardised and validated risk-of-bias instruments—optimised predominantly for clinical or epidemiological research paradigms—would likely have yielded spurious metrics incongruent with the inherently normative and conceptual dimensions of the evidence base analysed herein (Brunori et al., 2025; Htun et al., 2023).

2.9. Synthesis methods (PRISMA items 13, 15)

Owing to the inherent infeasibility of quantitative data aggregation, we employed a qualitative thematic synthesis integrated with rigorous normative mapping (Baralla et al., 2019; Bekkouche & de -Magistris, 2025). This methodological framework elucidated critical intersections between established food regulations and emergent digital platform jurisprudence, thereby facilitating a comprehensive cross-sectional analysis of the extant literature (Atik, 2022; Rehm et al., 2023). To address qualitative heterogeneity, evidence was systematically categorised into predefined thematic clusters that delineate the primary governance challenges inherent in e-commerce ecosystems (Cordero-Gutiérrez et al., 2025; Gonçalves et al., 2025).

2.10 Assessment of publication bias (PRISMA item 14)

To evaluate potential selective reporting bias, we implemented a systematic qualitative assessment of funding sources and institutional affiliations (Dokuzlu, 2016; Mascarello et al., 2024). We specifically distinguished between studies sponsored by the technology industry—which almost exclusively emphasise the benefits of traceability systems—and independent legal analyses that highlight critical compliance vulnerabilities (Kokole et al., 2025; Meng et al., 2019). This nuanced contextualisation facilitated a more rigorous and balanced interpretation of the extant literature identified within this review (Ryan et al., 2024).

2.10. Certainty of Evidence (PRISMA item 14)

Whilst a formal appraisal of the certainty of evidence via the GRADE system proved impractical given the non-clinical nature of the included studies, we adapted the GRADE-CERQual principles to evaluate the relevance of the legal argumentation and the temporal currency of the data (Munoz-Arcentales et al., 2020; Narayana et al., 2025). Consequently, our derived conclusions acknowledge the epistemic constraints intrinsic to literature situated at the nexus of accelerated technological innovation and reactive legislative frameworks (Christopoulos et al., 2023; Moosavy et al., 2025). This rigorous methodological architecture establishes the requisite foundation for the thematic synthesis and comprehensive mapping of results detailed in the subsequent section (González-Ceballos et al., 2020; Li et al., 2025).

2.11. Grey literature

The search was completed by querying the EUR-Lex database for regulatory acts, specifically regulations and directives, and jurisprudence from the Court of Justice of the European Union (CJEU). Furthermore, we systematically analysed official reports issued by the European Commission and the European Court of Auditors (ECA).

2.12. Outcome measures and data processing

The outcome measures reported in the individual studies were extracted and compared narratively, without pooling, due to heterogeneity.

2.13. Assessment of publication bias

Publication bias was addressed narratively by assessing the completeness of the sources and discussing the impact of the absence of grey literature where applicable.

3. Results

3.1. Study selection flow

The study selection process is presented in Fig. 1. The database search identified 1,597 records, from which duplicates were removed prior to screening. Title- and abstract-level screening excluded records that did not satisfy the predefined eligibility criteria. Full-text assessment was then conducted on the remaining reports, and 113 studies were retained for the final qualitative synthesis. No additional eligible studies were identified through backward snowballing. Overall, the PRISMA flow diagram documents a structured and sequential reduction from the initial search output to the final evidence base included in this review (Fig. 1).

3.2. Temporal distribution of the included literature

The temporal distribution of the included studies is shown in Fig. 2. The annual pattern indicates that the literature on artificial intelligence, digital labelling, and food traceability in the European and e-commerce context remained limited in the earlier years of the review period, followed by a marked expansion in more recent years. This trajectory suggests an acceleration of scholarly and policy-related interest in the field, plausibly associated with the simultaneous maturation of digital traceability technologies, the growth of online food commerce, and the increasing regulatory salience of transparency, interoperability, and platform accountability. The upward trend also indicates that this is a rapidly consolidating research domain rather than a mature and saturated body of literature.

3.3. Main publication sources

The principal publication sources are summarised in Fig. 3. The distribution across journals indicates that the evidence base is interdisciplinary, spanning food science, agri-food systems, sustainability, digital governance, and technology-oriented outlets. At the same time, the concentration of publications in a limited number of journals suggests that knowledge production in this area is being shaped by a relatively identifiable core of publication venues. This concentration is relevant from an interpretative standpoint, because it indicates that debates on AI-enabled traceability and digital labelling are not dispersed randomly across the literature, but are increasingly coalescing around journals that integrate food systems, digital transition, and regulatory analysis.

3.4 Keyword co-occurrence structure

The conceptual structure of the included literature is illustrated in Fig. 4 through the keyword co-occurrence network. The network reveals that the field is organised around a set of recurrent and strongly connected terms related to traceability, blockchain, artificial intelligence, digitalisation, sustainability, food safety, and supply-chain management. The prominence and interconnection of these terms indicate that the literature does not treat technological innovation, regulatory compliance, and food governance as isolated dimensions; rather, they emerge as mutually constitutive components of the same analytical space. The network structure further suggests that blockchain and AI frequently function as enabling technologies within a broader discourse on transparency, monitoring, and trust-building in digital agri-food systems.

3.5. Thematic structure of the field

The thematic map presented in Fig. 5 provides a higher-level representation of how the included literature is organised conceptually. The relative centrality and density of the thematic clusters indicate that some themes occupy a more established and structurally connected position within the knowledge base, whereas others remain more peripheral, emerging, or weakly consolidated. In substantive terms, the map confirms that the field is shaped by the intersection of several major thematic domains: technological innovation in traceability systems, digital governance and interoperability, food safety and consumer information, and broader sustainability-oriented transitions in agri-food systems. This thematic configuration supports the interpretation that the literature has evolved beyond purely technical problem-solving and increasingly engages with institutional, legal, and socio-economic implications.

3.6. Integrated interpretation of the descriptive evidence

The Figs. 2–5 demonstrate that the reviewed literature has expanded in recent years, is anchored in a recognisable interdisciplinary journal ecosystem, and exhibits a coherent conceptual structure centred on traceability, transparency, regulatory adaptation, and digital transformation. These descriptive findings reinforce the rationale for treating artificial intelligence and digital labelling not merely as technical innovations, but as components of a broader reconfiguration of governance in agri-food e-commerce.

3.7. Conceptual synthesis

This framework consolidates the main interpretative dimensions emerging from the included evidence and clarifies the functional relationships between technological infrastructures, traceability mechanisms, regulatory control, interoperability constraints, and governance outcomes. In contrast to the descriptive role of Figs. 2–5, which map the structure of the evidence base.

3.8. Risk of Bias Assessment

Risk of bias was assessed using appraisal tools selected according to the design of the included studies. Given the methodological diversity of the evidence base, study-specific criteria were applied to ensure that the assessment remained proportionate to the nature of each source and consistent with the objectives of the review. The evaluation focused on key domains including clarity of study objectives, adequacy of methodological description, transparency of data sources, coherence between methods and conclusions, and the extent to which regulatory or technological claims were supported by the presented evidence.

Overall, the included literature showed heterogeneous methodological quality. Empirical studies generally presented clearer analytical procedures and better-defined data sources, whereas conceptual, doctrinal, and policy-oriented publications more frequently exhibited limitations related to reproducibility, selective emphasis, or insufficient methodological transparency. In several cases, the interpretative strength of the conclusions exceeded the empirical grounding provided in the source material, particularly in papers addressing the transformative potential of artificial intelligence, blockchain, or digital product passport architectures.

4. Discussions

4.1. Critical Interpretation

Our systematic literature review identifies a fundamental transition in the architecture of agri-food supply chains within the European Union, marking a shift from passive, retrospective records to active, predictive traceability facilitated by artificial intelligence (AI) (Rossi et al., 2025; Singh et al., 2026; Sortino et al., 2023). This emerging paradigm demonstrates that digital labelling technologies, such as photosensitive sensors and smart packaging, no longer function as simple information carriers but as active nodes within a complex network of food quality and safety monitoring (Marvin et al., 2022; Wang et al., 2025; Zhang & Yan, 2025). Machine learning algorithms integrated into these traceability platforms enable the early identification of thermal anomalies or spoilage risks, thereby optimising the shelf life of perishable products within the e-commerce sector (Ahmadzadegan et al., 2020; Sapienza & Vedder, 2023; Xie et al., 2024). Consequently, digitalisation represents more than a technical modernisation; it is a strategic instrument that facilitates the alignment of commercial operations with the sustainability objectives stipulated in the European Green Deal (Di Gregorio et al., 2024; Georgescu et al., 2022; Manta, 2026).

Furthermore, the evidence indicates a profound convergence between technological innovation and regulatory requirements within the European e-commerce landscape (Di Carlantonio et al., 2024; Gori et al., 2026). As online food sales platforms proliferate, regulatory authorities encounter substantial challenges in asserting jurisdiction and verifying the compliance of pre-packaged products (Gori et al., 2026; Jia et al., 2024). The deployment of digital labels and Digital Product Passports offers a robust mechanism to circumvent these jurisdictional barriers, ensuring a continuous and verifiable data flow between manufacturers, e-commerce platforms, and end consumers (Evangelatos et al., 2025; Jiang et al., 2025). This information architecture enhances commercial transparency whilst augmenting the capacity of regulatory agencies to conduct remote official controls, thereby mitigating risks associated with food fraud and the distribution of non-compliant products (Burylo et al., 2023; Di Carlantonio et al., 2024; Li et al., 2024).

In parallel, the literature underscores the synergistic role of blockchain technology when coupled with AI to secure traceability data (Giannini et al., 2025; Nicolau & Petcu, 2026; Varavallo et al., 2022). The primary mechanism identified is the capacity of blockchain to guarantee the immutability of data captured by IoT sensors and processed by AI, establishing a distributed ledger that is inherently resistant to falsification (Barge et al., 2023; Toader et al., 2024; Zarbà et al., 2024). Such technological integration aligns with European Union initiatives to construct trust networks within the agri-food sector, where information asymmetries amongst supply chain actors have traditionally created systemic vulnerabilities (Chrysomallidis & Doukas, 2024; de Vries et al., 2023; Martínez-Castañeda & Feijoo, 2023). However, the efficacy of this framework remains fundamentally contingent upon the integrity of the data initially ingested into the system (the 'data oracle' problem), necessitating the implementation of rigorous validation protocols at the point of origin (Stoyanov, 2024; Stranieri et al., 2021).

4.2. Heterogeneity and variability

Conversely, a critical synthesis of current evidence reveals profound geographical and structural heterogeneity regarding the deployment of these technologies across European Union (EU) member states (Martínez-Castañeda & Feijoo, 2023; Staver, 2025; Tache, 2024). Extant research highlights a stark divergence between Western European nations, which leverage mature digital infrastructures and robust institutional frameworks, and their Eastern or Southern counterparts, where fragmented land ownership and capital constraints impede the integration of "Agriculture 5.0" paradigms (Andreghetto et al., 2025; Holzinger et al., 2024; Odobasa & Borzan, 2021; Staver, 2025). Such contextual variability suggests that whilst European digitalisation policies appear unified at the discursive level, their translation into national practice remains markedly divergent; this creates a fragmented traceability landscape that potentially undermines the cohesion of the single market (Chatzitheodoridis et al., 2025; Ehlers et al., 2022; Sekulic et al., 2025).

Furthermore, the literature demonstrates pronounced architectural variability amongst proposed and implemented traceability systems (Dhal & Kar, 2024; Villegas-Ch et al., 2025; Wagan & Sidra, 2026). Whilst certain studies propose computationally intensive models predicated on deep neural networks for food quality assessment, alternative research advocates for "lightweight blockchain" architectures and streamlined algorithms optimised for the processing constraints of field-deployed Internet of Things (IoT) devices (Dhal & Kar, 2024; Sapienza & Vedder, 2023; Villegas-Ch et al., 2025). This methodological heterogeneity reflects an intrinsic tension between the pursuit of maximal analytical precision and the imperative to develop scalable, energy-efficient, and economically viable systems tailored to small-scale producers (Ahmad et al., 2024; Garcia-Gallego et al., 2025).

Moreover, such variability is acutely manifested within national regulatory frameworks governing data stewardship and the application of artificial intelligence (Lenarczyk et al., 2025; Stoyanov, 2024; Terzis & Santamaria Echeverria, 2023). Whilst initiatives such as the European Data Space seek to harmonise information exchange, the practical implementation of interoperability standards remains inconsistent across the bloc (Roussaki et al., 2023; Urdu et al., 2024). Disparate interpretations of regulations concerning commercial data confidentiality and legal liability for erroneous automated decisions exacerbate legal uncertainty, potentially stifling the widespread adoption of integrated digital platforms within the agri-food sector (Blazo, 2022; Gori et al., 2026; Solaiman, 2023).

4.3. Contradictions and divergences

Systematic literature reviews have identified fundamental discrepancies concerning the socio-economic implications of supply chain digitalisation, particularly regarding the cost–benefit equilibrium for small and medium-sized enterprises (SMEs) and smallholder farmers (Dela Cruz et al., 2025; Garcia-Gallego et al., 2025; Stranieri et al., 2021). One prominent perspective posits that e-commerce platforms and artificial intelligence (AI)-driven traceability mechanisms democratise market access, empowering small-scale producers to authenticate product quality and command premium pricing (Ahmad et al., 2024; Garcia-Gallego et al., 2025). Conversely, contrasting evidence suggests that stringent technical requirements and the prohibitive costs associated with digital infrastructure implementation may exert an exclusionary pressure, thereby consolidating the market dominance of large-scale agri-food conglomerates that possess the requisite capital to adhere to emerging digital labelling standards (Rodriguez & Piccoli, 2024; Stranieri et al., 2021).

Diverging from the prevailing techno-optimism regarding adoption, substantial heterogeneity exists in consumer perceptions of digital labelling and algorithmic traceability (Fraser & Balcombe, 2018; Martín-Cervantes et al., 2025; Mazzù et al., 2021). Whilst increased information transparency is conventionally hypothesised to bolster consumer confidence, empirical findings indicate that the proliferation of QR codes and intricate provenance data may inadvertently precipitate cognitive overload or consumer confusion (Fraser & Balcombe, 2018; Perret & Skretkowicz, 2025). Furthermore, an unresolved tension persists between the consumer mandate for comprehensive supply chain transparency and a concomitant reluctance to divulge personal data to e-commerce platforms, illustrating a pronounced privacy paradox within the digital food ecosystem (Mazzù et al., 2021; Palka et al., 2024).

Simultaneously, a fundamental dissonance remains between the accelerated trajectory of technological innovation and the inherent inertia of regulatory frameworks—a phenomenon frequently characterised as a perception–reality gap (Gilbert et al., 2021; Nicolau & Petcu, 2026; Singh et al., 2025). Whilst AI algorithms undergo continuous refinement through adaptive learning processes, European legislative frameworks—specifically those governing food safety and official controls—frequently remain anchored in static, traditional assessment models (Burylo et al., 2023; Deepika et al., 2026; Gilbert et al., 2021). This institutional asynchrony engenders a regulatory vacuum wherein novel smart labelling and predictive risk-assessment tools are deployed without standardised algorithmic validation protocols, thereby complicating questions of legal liability in the event of food safety incidents (Gori et al., 2026; Sapienza & Vedder, 2023; Solaiman, 2023).

4.4. Limitations of the evidence and review

Interpretation of these findings necessitates a critical appraisal of the inherent limitations within the primary evidence base (Karkanias et al., 2026; Kumar et al., 2024; Shete et al., 2025). A substantial proportion of the evaluated literature relies upon conceptual frameworks, controlled simulations, or restricted case studies; consequently, there remains a conspicuous dearth of longitudinal empirical research assessing the performance of artificial intelligence (AI) and blockchain architectures under authentic market conditions over protracted intervals (Karkanias et al., 2026; Sapienza, 2022; Zarbà et al., 2024). Furthermore, the risk of bias permeates numerous reviewed studies, primarily stemming from the selective reporting of favourable outcomes and a pervasive lack of transparency concerning the datasets employed for algorithmic training. Such methodological opacity constrains the reproducibility and generalisability of these conclusions across the heterogeneous European agri-food landscape (Kumar et al., 2024; Shete et al., 2025; Wagan & Sidra, 2026).

Beyond the primary evidence, the methodological framework of this systematic review entails specific constraints that warrant transparent acknowledgement (Amentae & Gebresenbet, 2021; Juliá-Igual et al., 2025; Zyoud & Zyoud, 2025). Confining the search parameters to English-language publications within primary academic databases may have inadvertently excluded pertinent grey literature, national governmental reports, or studies published in the vernacular languages of European Union (EU) member states. These sources might have yielded critical insights into idiosyncratic regional implementation challenges (Juliá-Igual et al., 2025; Zyoud & Zyoud, 2025). Moreover, the accelerated evolutionary trajectory of the technological sector renders certain data rapidly obsolete, whilst cutting-edge innovations emerging from the private sector may not yet be reflected within the peer-reviewed corpus (Amentae & Gebresenbet, 2021; Muehlematter et al., 2021).

Consequently, the absence of a formalised assessment regarding the certainty of evidence—such as the Grading of Recommendations Assessment, Development and Evaluation (GRADE) system—exerts a substantial influence on the final conclusions, necessitating a rigorous calibration of the resulting academic discourse (De Sutter et al., 2023; Lin et al., 2025; Muehlematter et al., 2021). Given the current lack of standardised metrics to verify the absolute robustness of these technological interventions, assertions regarding the efficacy of AI in eliminating food fraud or guaranteeing seamless traceability must be approached with considerable caution (Bogadi et al., 2025; Evangelatos et al., 2025; Li et al., 2024). Whilst extant evidence indicates transformative potential and identifies promising avenues for optimisation, it remains insufficient to support definitive verdicts concerning the categorical superiority of these systems over conventional control methodologies. Further validation within complex operational environments is therefore imperative (De Sutter et al., 2023; Lin et al., 2025; Sapienza & Vedder, 2023).

4.5. Theoretical and practical implications

Theoretically, these findings refine the conceptual framework of the "Agriculture 5.0" paradigm and digital food environments (Balaska et al., 2023; Holzinger et al., 2024; Mugion et al., 2026). The synthesised literature necessitates a shift beyond technological determinism, characterising traceability as a complex sociotechnical system wherein algorithms, sensors, regulatory frameworks, and human behaviours co-evolve (Ahmad et al., 2024; Holzinger et al., 2024). This expanded theoretical lens mandates that future investigations integrate models from behavioural economics and the sociology of innovation to elucidate the mechanisms underlying digital label adoption; importantly, this requires transcending the reductive assumption that technical efficiency inherently ensures social acceptability or commercial viability (Martín-Cervantes et al., 2025; Mugion et al., 2026; Perret & Skretkowicz, 2025).

Practically, the implications for policymakers and supply chain stakeholders are immediate, necessitating coordinated strategic action (Jiang et al., 2025; Roussaki et al., 2023; Urdu et al., 2024). The efficacious implementation of the Digital Product Passport and smart labelling systems demands the accelerated formulation of semantic and technical interoperability standards across the European Union to preclude the emergence of fragmented, incompatible data silos (Evangelatos et al., 2025; Jiang et al., 2025; Urdu et al., 2024). Furthermore, regulatory bodies must establish rigorous guidelines for the validation of artificial intelligence (AI) algorithms deployed in food risk assessment, ensuring these systems are transparent, explainable (Explainable AI), and devoid of algorithmic biases that might disproportionately disadvantage specific producers or geographical regions (Khurana et al., 2026; Sapienza & Vedder, 2023; Wagan & Sidra, 2026).

Consequently, regarding enforcement within the e-commerce sector, our results underscore the necessity of reconfiguring official control strategies (Di Carlantonio et al., 2024; Jia et al., 2024; Kong et al., 2024). National food safety agencies should leverage integrated web-scraping tools and AI-driven predictive analytics to proactively monitor e-commerce platforms, thereby identifying anomalous labelling patterns or discrepancies in declarations of origin (Di Carlantonio et al., 2024; Kong et al., 2024; Panni et al., 2026). This paradigm shift from reactive physical inspections to proactive digital audits will likely augment the capacity of authorities to oversee the vast scale of cross-border transactions, whilst simultaneously safeguarding public health and maintaining the integrity of the European single market (Bogadi et al., 2025; Burylo et al., 2023; Jia et al., 2024).

4.6. Integrative synthesis and meta-interpretation

Fundamentally, a meta-interpretation of the aggregated data demonstrates that artificial intelligence (AI) and digital labelling function not merely as logistical optimisation tools, but as foundational mechanisms for the governance and enforcement of European policy frameworks (Kostic et al., 2026; Manta, 2026; Parra-López & Carmona-Torres, 2026). The integration of these technologies enables the seamless translation of abstract normative requirements—exemplified by the European Green Deal and circular economy strategies—into quantifiable parameters subject to real-time monitoring (Bandi et al., 2026; D'Amico et al., 2022; Georgescu et al., 2022). A primary mechanism identified across the analysed themes is the "datafication" of trust: the conversion of quality, provenance, and food safety from reputation-based attributes into cryptographically verifiable and algorithmically analysable metadata (Sapienza & Vedder, 2023; Toader et al., 2024; Zarbà et al., 2024). This paradigm shift suggests that the future competitiveness of the European Union (EU) agri-food sector will be determined not solely by the intrinsic quality of the physical product, but by the integrity and granularity of the data flows accompanying it across e-commerce platforms (Gori et al., 2026; Manta, 2026; Panagos et al., 2025).

Notably, whilst digital architectures promise enhanced resilience within food systems, substantial areas of uncertainty persist that necessitate further empirical investigation (Marti, 2021; Myshko et al., 2024; Tausová et al., 2026). Specifically, it remains unclear how the extensive computational infrastructure required to sustain blockchain networks and sophisticated AI models can be reconciled with overarching carbon footprint reduction targets; consequently, a risk exists that digital solutions may generate unforeseen negative environmental externalities (Bandi et al., 2026; Kiskira et al., 2026; Zafeiriou et al., 2025). Furthermore, the mechanisms required to safeguard consumer cognitive sovereignty against the influence of recommendation algorithms and hyper-personalised labelling necessitate urgent legal clarification (Branda & Ciccozzi, 2026; Rojano et al., 2025). These epistemic and normative lacunae provide the impetus for formulating applied conclusions and strategic recommendations designed to steer the digital transition of the European agri-food sector in an equitable and sustainable manner.

4.7. Limitations of the review

Principal limitations of this review include the absence of a formal assessment of the risk of bias utilising a validated instrument, which potentially constrains the robustness of the conclusions and the generalisability of the results.

5. Conclusions

In summary, this systematic review indicates a profound structural transformation within European Union (EU) agri-food supply chains, characterised by a transition from passive, purely documentary traceability towards an active, dynamic, and predictive paradigm. This evolution, underpinned by the integration of artificial intelligence (AI) and advanced digital labelling technologies, suggests a fundamental redefinition of the ontological framework of food traceability within the burgeoning e-commerce landscape. Unlike conventional methodologies, wherein information accompanied the product in a static and frequently fragmented format, emergent technological architectures transform the label from an inert repository of data into an active agent of regulation, communication, and continuous surveillance. This paradigm shift transcends the mere technical modernisation of logistical infrastructure, emerging instead as a critical strategic instrument for surmounting the jurisdictional barriers inherent in transnational digital markets. The synthesised data suggest that the deployment of machine learning algorithms and digital product passports may significantly facilitate the alignment of commercial practices with the sustainability, transparency, and circular economy objectives articulated in the European Green Deal. Consequently, the convergence of technological innovation and stringent regulatory requirements offers a robust conceptual framework for optimising food governance, although the empirical efficacy of these complex systems remains contingent upon the quality, security, and interoperability of data harvested across the entire agri-food value chain. Furthermore, a critical synthesis of the extant evidence suggests that the successful deployment of these digital instruments in enforcing trade regulations necessitates a systemic approach capable of integrating rigorous food safety requirements with the imperatives of data sovereignty and consumer privacy. Whilst emerging technologies offer extensive real-time monitoring capabilities and the early detection of anomalies or fraudulent activities, their large-scale implementation within the European Union faces substantial governance and standardisation challenges. Our analysis indicates that the absence of unified technical protocols and the fragmentation of national legislative frameworks may significantly attenuate the capacity of artificial intelligence to ensure seamless and automated regulatory compliance within the e-commerce environment. Moreover, whilst digital passports and intelligent labels promise granular visibility throughout the product life cycle, the specific mechanisms through which these tools might effectively harmonise disparate regulations at a global scale—extending beyond the internal borders of the European Union—remain insufficiently elucidated in the current literature. This normative and technical ambiguity underscores the necessity for analytical rigour in assessing the long-term impact of digitalisation on global food security, suggesting that technological innovation must be complemented by sustained normative diplomacy. Nevertheless, this review identifies substantial epistemic and practical constraints, most notably a significant lacuna in assessing the differential impact of these technologies across diverse economic cohorts within the supply chain. Whilst academic and policy discourse frequently emphasises the macro-systemic advantages of digitalisation, current evidence is insufficient to provide a granular understanding of how high implementation costs and technical complexities affect smallholders and local producers relative to large-scale transnational logistical networks. This structural asymmetry suggests an inherent risk of digital marginalisation, whereby entities with constrained financial and technological resources may be excluded from a European e-commerce market increasingly defined by stringent traceability standards. The paucity of rigorous comparative studies and meta-analyses quantifying these economic and operational disparities represents a significant weakness in the current state of knowledge. Therefore, the uncritical adoption of AI-driven solutions, without due consideration for the technological absorption capacity of small-scale producers, could precipitate unintended competitive distortions, thereby undermining the principles of equity, social cohesion, and agricultural diversity that European sustainability policies are designed to safeguard and promote. Consequently, the findings of this systematic review necessitate a strategic recalibration of European public policy, advocating for a transition from the imposition of abstract technological mandates towards the development of inclusive, flexible regulatory frameworks adaptable to empirical realities. It is imperative that future legislative initiatives incorporate specific financial and technical support mechanisms to facilitate the adoption of digital labelling by micro-agricultural enterprises, thereby ensuring an equitable and sustainable digitalisation of the entire sector. Prospective research should prioritise empirical investigations and comparative studies focused on detailed cost-benefit analyses of AI implementation among small-scale producers, alongside assessments of the interoperability of traceability systems within complex extra-EU jurisdictional contexts. Recognising the inherent limitations of the current evidence base and the requirement for continuous validation, it is evident that the maturation of this field demands a deeply multidisciplinary approach capable of reconciling algorithmic innovation with the socio-economic realities of European agriculture. This shift in methodological and policy perspective will provide the essential foundation for future scientific inquiry to translate the theoretical potential of digital traceability into practical, equitable, and globally applicable solutions. Overall, the results suggest patterns aligned with the study objectives. Future research should validate these observations in larger and more diverse settings.

Declarations

Ethical Considerations

Not applicable. This study is based exclusively on published literature.

Data Availability Statement

All data extracted from the constituent studies are available within the Supplementary Information. Furthermore, detailed search strings and methodological evaluation protocols are available from the corresponding author upon reasonable request.

Declaration of author contributions (CRediT)

The sole author was responsible for conceptualisation, methodology, investigation, data curation, formal analysis, validation, visualisation, and project administration. Additionally, the author undertook the original draft preparation and the subsequent review and editing of the manuscript. The author assumes full accountability for the scientific content, the interpretation of results, and the final version of the manuscript.

AI Use Declaration

Artificial intelligence-based tools were employed exclusively for linguistic refinement, encompassing grammatical corrections, orthographic standardisation, and the enhancement of prose clarity. No generative AI systems were utilised to produce scientific content, execute data extraction, perform statistical analyses, or inform the interpretation of findings. The authors independently formulated all methodological frameworks, synthesised the data, and derived all conclusions; consequently, the authors retain full accountability for the accuracy and intellectual integrity of this work.

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Conflict of Interest

The author declares no competing financial, professional, or personal interests that could potentially influence the objectivity and impartiality of the findings reported in this manuscript.

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Figures

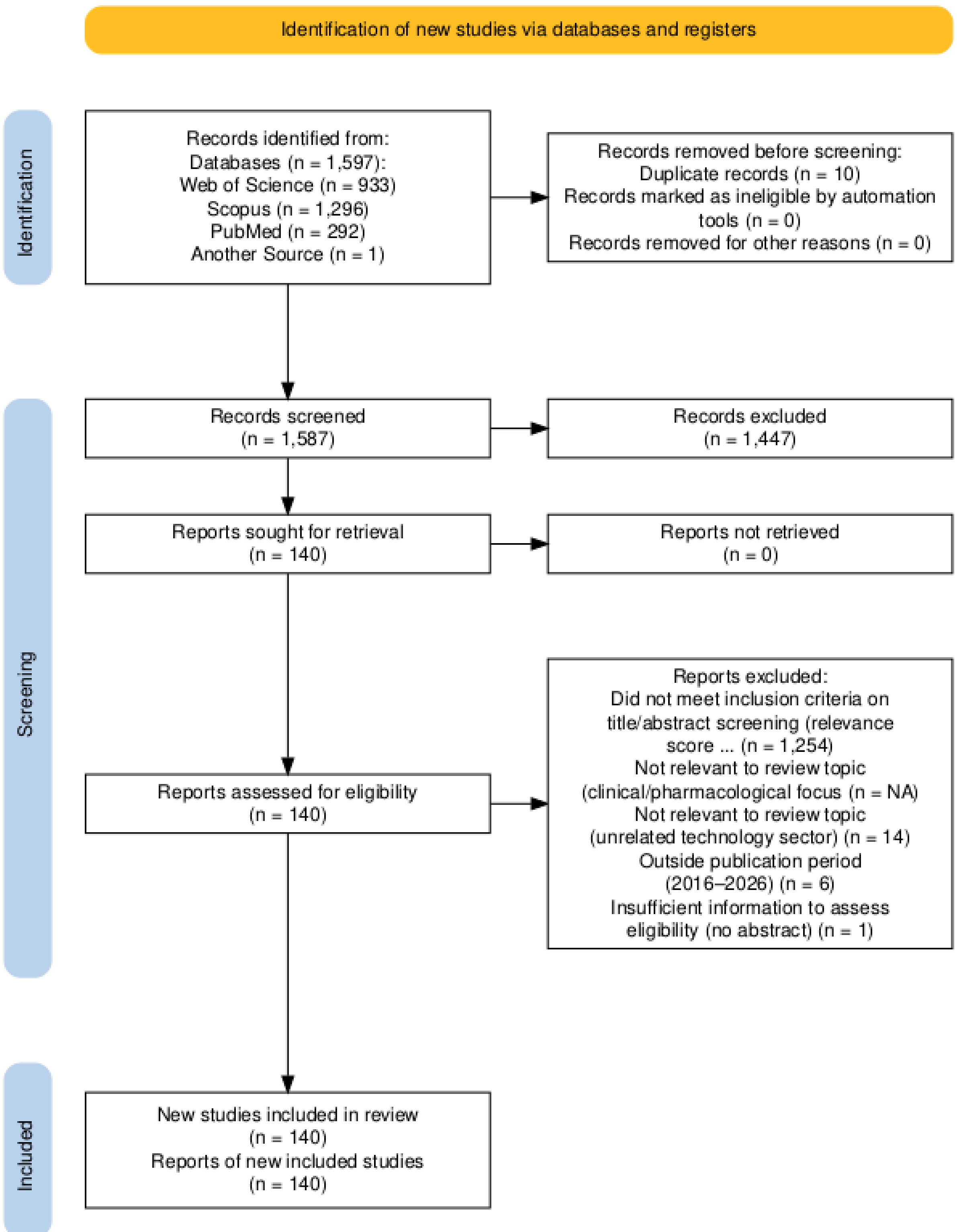

Figure 1

PRISMA 2020 flow diagram of the study selection process. The diagram summarizes identification, screening, eligibility assessment, and final inclusion of studies retrieved from Web of Science, Scopus, PubMed, and additional sources. After duplicate removal and title/abstract screening, 140 studies met the eligibility criteria and were included in the review.

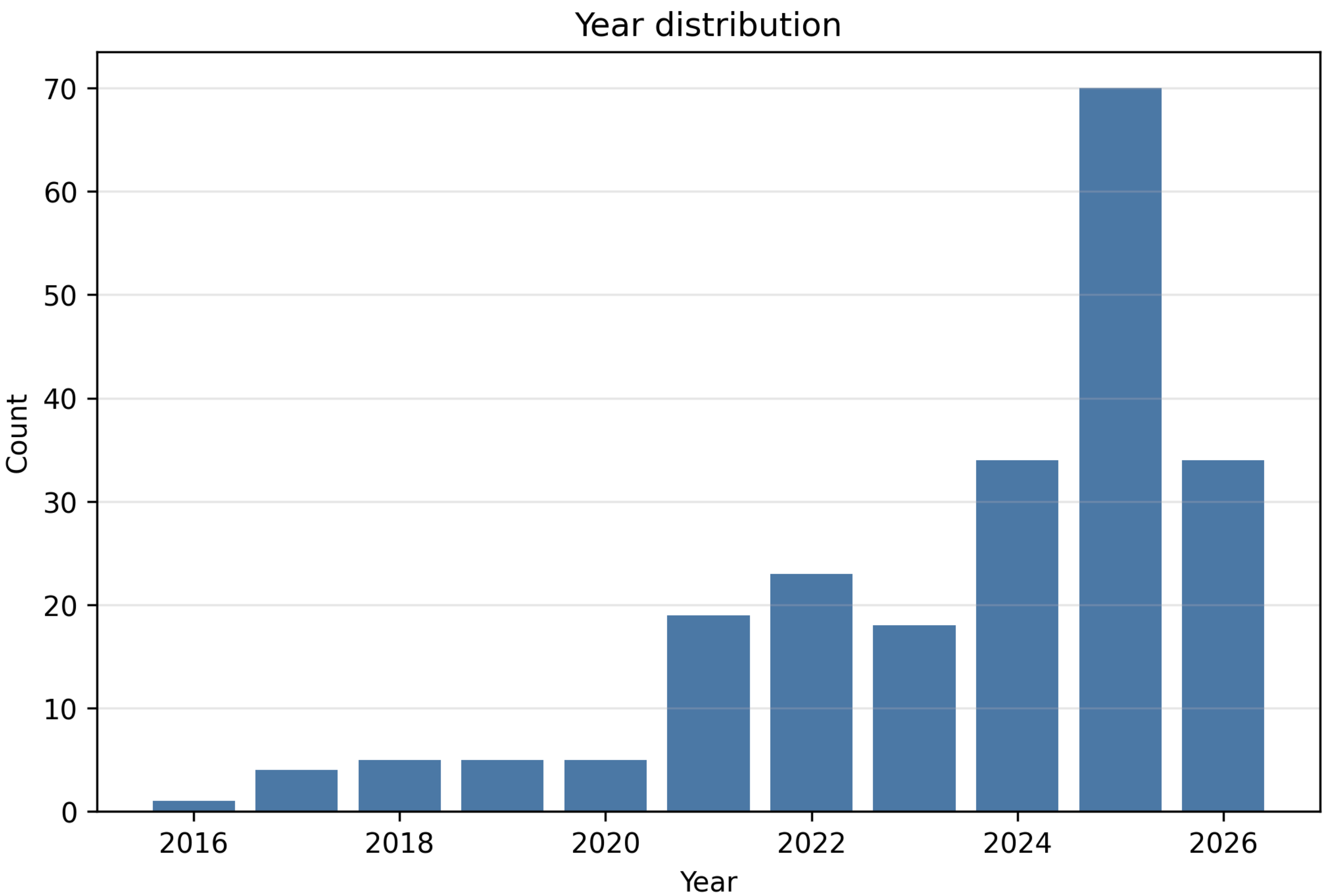

Figure 2

Annual distribution of included studies published between 2016 and 2026. The figure shows the temporal evolution of the literature, with a marked increase in publication output in the most recent years and a peak in 2025, indicating growing research interest in the topic.

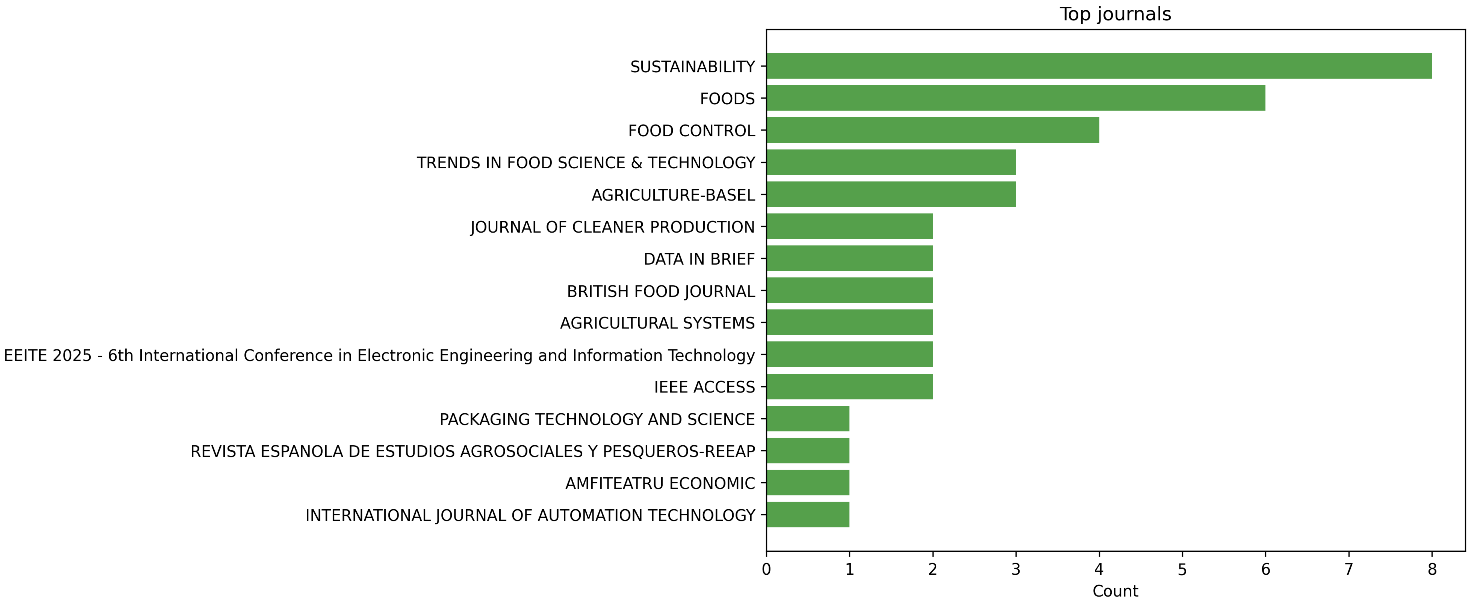

Figure 3

Most productive journals publishing studies included in the review. The bar chart presents the leading source titles by number of included articles, highlighting Sustainability, Foods, and Food Control as the most frequent publication outlets within the analyzed corpus.

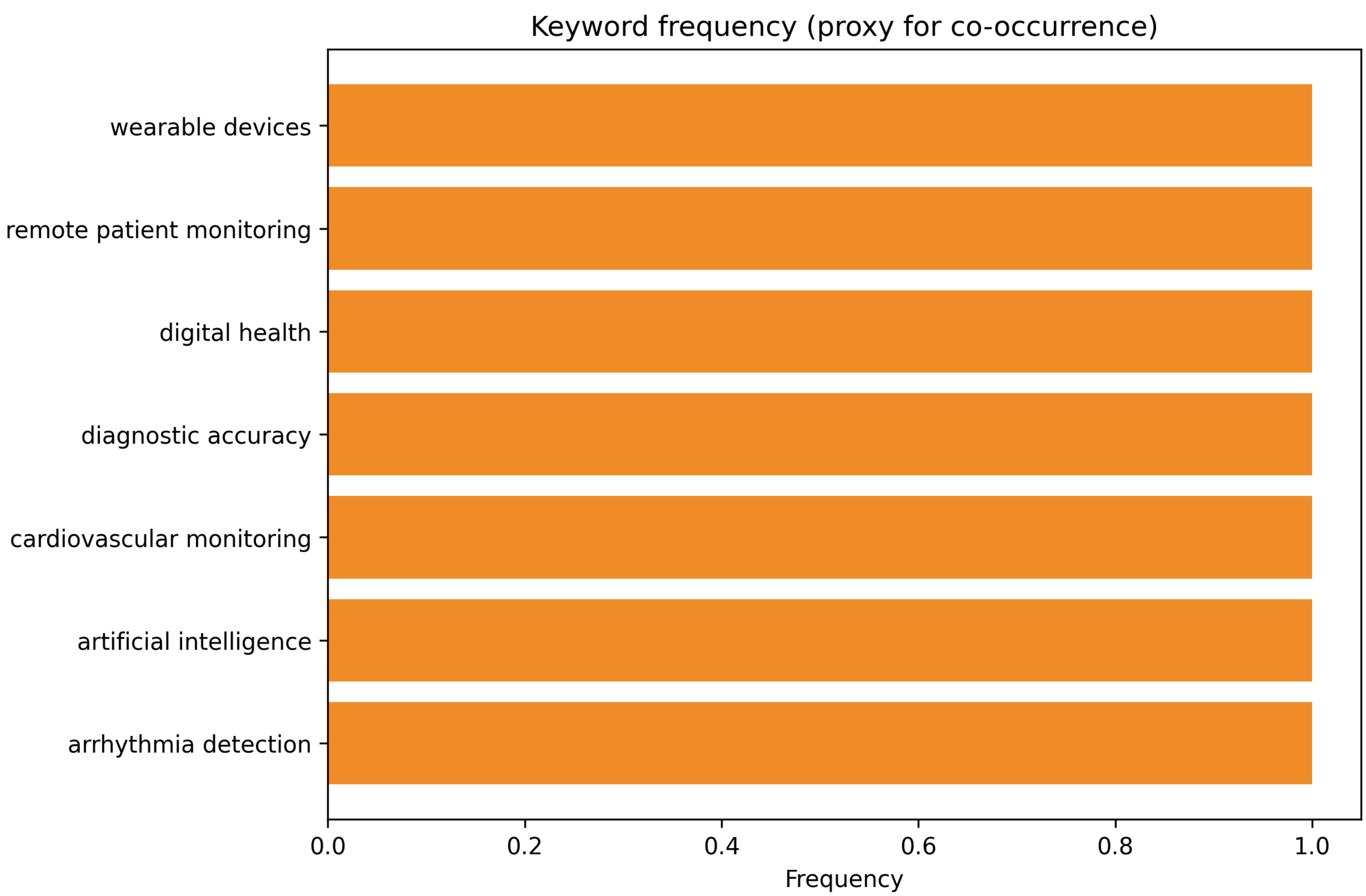

Figure 4

Most frequent author keywords identified in the included studies. The chart presents the dominant terms used across the literature as a proxy for keyword co-occurrence patterns, emphasizing recurring research topics such as wearable devices, remote patient monitoring, digital health, diagnostic accuracy, cardiovascular monitoring, artificial intelligence, and arrhythmia detection.

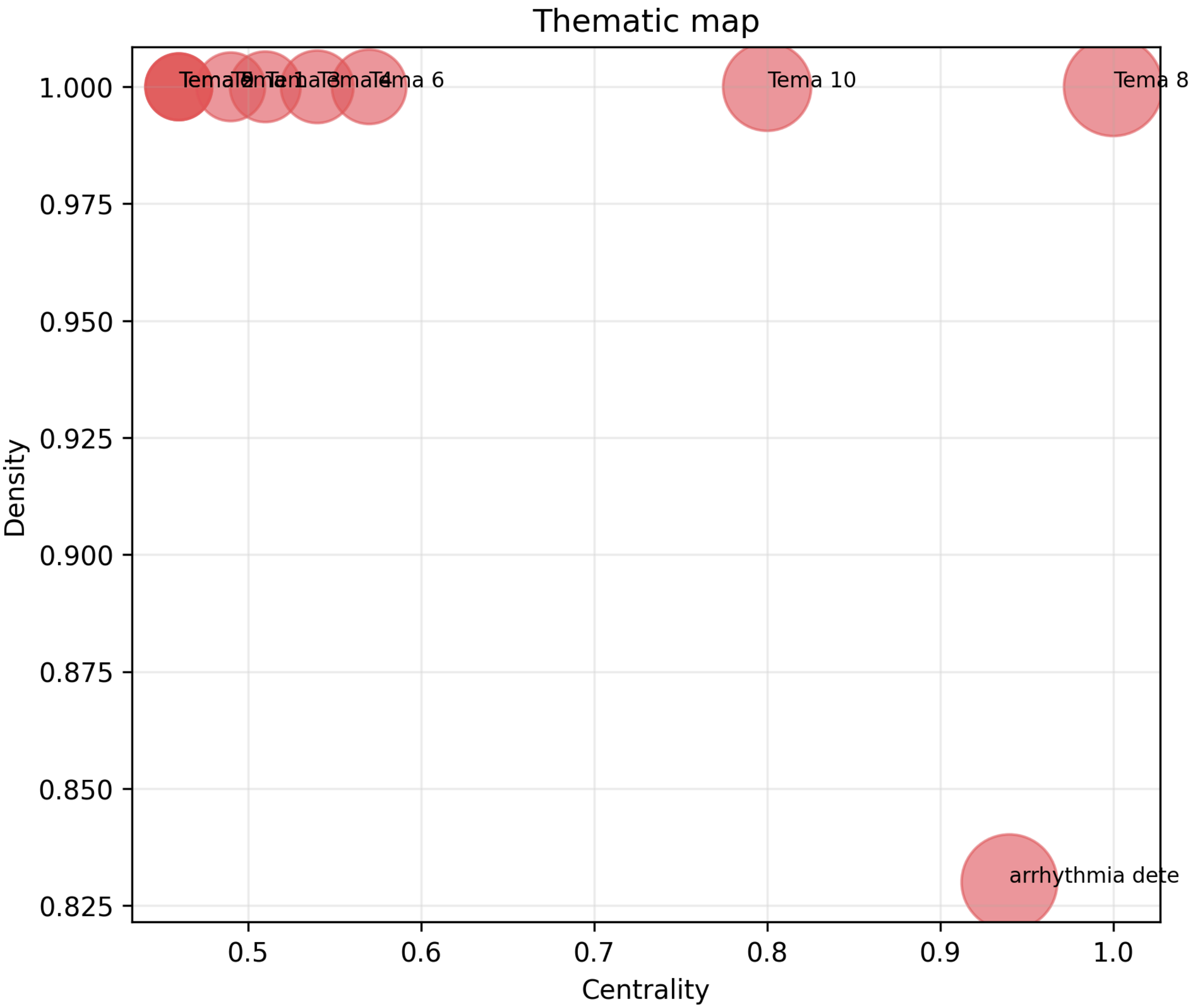

Figure 5

Thematic map of the conceptual structure of the included literature. Bubble size reflects the relative prominence of each theme, while the position on the centrality and density axes indicates its degree of relevance within the field and its level of internal development. Themes located toward the upper-right region represent well-developed and influential topics, whereas themes with lower centrality or density indicate more isolated or emerging research directions.