

TRAZABILIDAD INTELIGENTE DE ALIMENTOS MEDIANTE BLOCKCHAIN Y SENSORES IOT: REVISIÓN SISTEMÁTICA DE SU APLICACIÓN EN CADENAS DE SUMINISTRO AGROINDUSTRIALES

SMART FOOD TRACEABILITY USING BLOCKCHAIN AND IoT SENSORS: A SYSTEMATIC REVIEW OF ITS APPLICATION IN AGROINDUSTRIAL SUPPLY CHAINS

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RESUMEN: La seguridad alimentaria y la confianza del consumidor son clave para el comercio internacional, pero las cadenas de suministro tradicionales presentan vulnerabilidades. El uso combinado de blockchain y el Internet de las Cosas (IoT) ofrece una solución eficaz, garantizando trazabilidad y monitoreo continuo de productos, lo que previene fraudes y asegura su calidad. Este estudio sistemático de la literatura, que se ha adherido a las directrices PRISMA, se dedica a evaluar la madurez actual de la incorporación conjunta de blockchain e IoT en la trazabilidad alimentaria. Mediante búsquedas sistemáticas en Scopus y Web of Science se localizaron 65 investigaciones pertinentes; de éstas, 30 fueron elegidas para un examen detallado. Los hallazgos presentados evidencian que la integración sincronizada de las tecnologías estudiadas, lejos de representar únicamente la acumulación de componentes aislados, genera un registro de producto que es simultáneamente verificable y accesible, lo que, a su vez, refuerza la transparencia y la seguridad alimentaria. A esta contribución se suman incrementos medibles en eficiencia operativa, reducciones voluminosas en costos derivados de desperdicios y un notable afianzamiento de la confianza del consumidor. Sin embargo, las evidencias acumuladas revelan la existencia de barreras que no pueden ser ignoradas: la escalabilidad de las arquitecturas implementadas, la interoperabilidad entre entornos heterogéneos, la carga de inversión inicial necesaria y la dependencia de infraestructuras tecnológicas sostenibles a largo plazo. A partir de lo anterior, se sostiene que la trazabilidad alimentaria inteligente, sustentada en tecnologías de contabilidad distribuida y de Internet de las Cosas, representa un avance ineludible para la administración moderna de las cadenas de suministro alimentario, al tiempo que admite la restricción del fraude, el refuerzo de la seguridad alimentaria y la contribución al cumplimiento de los Objetivos de Desarrollo Sostenible.

Palabras clave: Trazabilidad de alimentos, blockchain, internet de las cosas (IoT), cadenas agroindustriales

ABSTRACT: Food security and consumer trust are key to international trade, but traditional supply chains present vulnerabilities. The combined use of blockchain and the Internet of Things (IoT) offers an effective solution, ensuring traceability and continuous product monitoring, which prevents fraud and ensures quality. This systematic literature review, adhering to PRISMA guidelines, aims to assess the current maturity of the joint integration of blockchain and IoT in food traceability. Through

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systematic searches in Scopus and Web of Science, 65 relevant studies were identified, of which 30 were selected for detailed examination. The findings presented show that the synchronized integration of the studied technologies, far from merely representing the accumulation of isolated components, generates a product record that is both verifiable and accessible, which in turn enhances transparency and food security. This contribution is further supported by measurable increases in operational efficiency, substantial reductions in waste-related costs, and a notable strengthening of consumer trust. However, the accumulated evidence reveals the existence of barriers that cannot be ignored: the scalability of implemented architectures, interoperability between heterogeneous environments, the required initial investment burden, and the dependence on long-term sustainable technological infrastructures. Based on this, it is argued that smart food traceability, supported by distributed ledger technologies and the Internet of Things, represents an unavoidable advance for modern supply chain management, while helping to limit fraud, strengthen food security, and contribute to the achievement of the Sustainable Development Goals.

Keywords: Food traceability, blockchain, Internet of Things (IoT), agro-industrial chains

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INTRODUCTION

Food safety and quality represent enduring challenges in an interconnected global context. Contemporary agroindustrial supply chains, which link producers from different latitudes with consumers dispersed across the planet, show an inherent complexity and, frequently, scarce transparency (1), (2). Said lack of clarity feeds fraud, contamination, and the propagation of foodborne diseases, infrastructures that compromise public health, generate enormous monetary losses, and undermine the confidence of consumers in the market (3), (4).

Traceability whose meaning is consigned in the norm ISO 22005:2007 as the ability to follow the trajectory of a food throughout all the stages of the chain is governed as the essential strategy to contain such dangers. Nevertheless, the current schemes of traceability, which are supported on manual registers or on centralized databases, suffer from slowness and are susceptible to manipulation (5), (6). The trajectory to identify the focus of a contamination outbreak can prolong itself for weeks, a delay that complicates the management of the crisis and limits the possibilities of a timely response (7).

In this framework, the industry has directed its attention toward the elaboration of technological platforms of vanguard. The synergy between the blockchain and the Internet of Things is profiled as one of the most promising tools to reconfigure the food traceability, upon permitting the decentralized register and the printing of data in real time (8), (9). The first, initially associated with the cryptocurrencies, operates as a distributed register that results analogous to a ledger, where each operation, such as

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the movement of a product from the field to the packaging line, is inserted in a block whose modification demands the agreement of all the nodes involved.

Such mechanism produces an uninterrupted narrative about the logisticized object, which exhibits, at a time, guarantees of security, levels of transparency, and faculties of audit for each one of the nodes of the distributive network (10), (11). The inalterability that distinguishes this architecture constitutes the obstacle that brakes the undesired substitutions and certifies the authenticity of the information. The Internet of Things, in its turn, constitutes the link that interconnects the material domain and the digital plane.

By means of IoT sensors, such as thermometers, humidity registrars, and GPS equipment, the critical parameters of the products are sampled in an autonomous mode and in continuous during the entire cold chain (12), (13). An illustrative case is produced in a refrigerated trailer, where a digital thermometer transmits the temperature at regular intervals; in case that the momentary value surpasses a stipulated critical value, a smart contract in the Blockchain is activated and registers the incident as a discrepancy in the transport history.

In this framework, the automation reduces the probability of errors induced by the operator during the register of data and provides a safeguard of the information that is simultaneously uninterrupted and susceptible of audited verification (14), (15). The intersection between the Internet of Things and the infrastructures of blockchain — concept that is designated as smart traceability— integrates to the storage the faculty of validating the data in an autonomous manner and in real time, which, in its turn, reinforces the total security of the transactions and elevates the level of confidence of the consumer (16), (17).

The principal motivation that orients this study is the pressing need to articulate and amplify the corpus of knowledge about this disruptive technology. Although the interest of the industry and some field experiments such as the tracking of the pork meat on the part of Walmart in China (18), have multiplied, the academic literature continues presenting a fragmentary character. With this backdrop, the present work is formulated as an effort to remedy this lagoon by means of a systematic review that analyzes in a rigorous manner the advantages, the challenges, and the current state of the adoption of the technology.

It results, therefore, inescapable to advance beyond the mere enunciation of the conceptual benefits and to submit to scrutiny the concrete barriers that limit a generalized implantation, among which are counted the high initial costs and the lack of interoperability between heterogeneous informatic architectures (19), (20).

The axial axis of this investigation analyzes the potential that the synergistic convergence between the technologies of distributed register and the networks of sensors of interconnected devices presents to solve the structural limitations of the systems of traditional traceability in the agroindustrial sector. The purpose consists in discerning both the obstacles and the decisive opportunities that arise upon integrating both technologies in the agri-food supply chains.

Such purpose orients the execution of a systematic review destined to quantify the impact that the concatenated interaction of both platforms exercises over the traceability of the food products; to grade the benefits that emerge from said interdependence; to cartograph the obstacles that persist and to delineate the future avenues of investigation. The final purpose is to foment a food industry capable of articulating, in a concurrent mode, a greater security, transparency, and efficiency.

MATERIALS AND METHODS

The present work implements a systematic review of the literature, scientific procedure that, by means of defined and susceptible of repetition stages, makes possible the localization, screening, and impartial condensation of the accumulated evidence around a previously sectorized phenomenon. With the end of guaranteeing both the transparency and the methodological robustness, the recommendations prescribed by the PRISMA declaration (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) have been respected. This operative scheme was executed in a series of four successive stages: Identification, Screening, Eligibility, and Inclusion. Next, the procedure followed in each one of said stages is exposed.

Before initiating the collection of data, the research question that would guide each stage of the inquiry was posed with clarity: How the interaction between the Blockchain technology and the sensors of Internet of Things reinforces the traceability, the security, and the efficiency in the agroindustrial supply chains, and what challenges and possibilities predominate in the race toward their generalized adoption. With this question as axis, the specific objectives of the study were structured, which oriented the curation and selection of the documentary sources that, in a systematic form, fed the posterior argumentation.

Search strategy and data sources

The bibliographic collection was carried out in a systematic form in academic repositories and recognized scientific platforms: Scopus, Web of Science, ScienceDirect, and IEEE Xplore. To assure the validity of the evidence, it was limited to documents published between 2018 and 2024, period that coincides with the acceleration of the advances in Blockchain and IoT.

A search string was designed that articulated key concepts and boolean connectors, in such a manner that an extensive coverage was achieved and, at the same time, a rigorous filtering that excluded the non-pertinent production.

Table 1. Literature Search Strategy.

Database	Search string	Period
Scopus	("blockchain" AND "food traceability") OR ("IoT" AND "food supply chain")	2018-2024
Web of Science	("smart traceability" AND "agro-industry") OR ("distributed ledger" AND "food safety")	2018-2024
ScienceDirect	("IoT sensors" AND "agrifood supply chain") OR ("blockchain" AND "food supply chain")	2018-2024

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IEEE Xplore	("blockchain" AND "food traceability")	2018-2024
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Analysis: Table 1 condenses the search strategy adopted in the present review, elaborated around four scientific databases of first level (Scopus, Web of Science, ScienceDirect, and IEEE Xplore) and encompassing the interval 2018–2024 to incorporate recent and pertinent investigations. The search strings combine fundamental vocabularies such as “blockchain”, “IoT”, and “food traceability” through boolean operators, in such a manner that the indexed literature is recovered that explores with clarity the articulation of these technologies in the traceability and governance of agri-food chains. Such methodology, concordant with the PRISMA prism, guarantees a systematic, reproducible search directed to results of significance.

Selection criteria (screening and eligibility)

The management and filtering of the results was carried out in two successive and defined stages.

Table 2. Inclusion and Exclusion Criteria.

PRISMA Phase	Process	Criteria
Screening	Elimination of duplicates. Review of titles and abstracts.	Inclusion: Articles about traceability in agroindustrial chains, models, prototypes or reviews. Exclusion: Texts considered for the present analysis do not include contributions of op-ed character, editorial pieces, abstracts that do not accompany the complete body of the work or any segment that lacks autonomous argumentative development.
Eligibility	Complete reading of the text. Verification of relevance and quality.	Inclusion: Those studies that present rigorous empirical evidence about the economic, social, and environmental benefits of the smart traceability were considered, as well as those that discuss in a systematic manner the technical and organizational challenges that the agri-food chains face upon implementing such systems. Exclusion: Those works that, even if they mention the traceability, lack a specific analysis directed to the particularities of the agri-food sector, limiting themselves to a general framework of information technologies, were discarded.

Analysis: Table 2 systematizes the inclusion and exclusion criteria implemented according to the stages of screening and eligibility of the PRISMA model, assuring, in

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this mode, the exhaustive selection of the pertinent bibliography. During the first phase of screening, the duplicate registers were eliminated and, next, the titles and abstracts were evaluated, admitting uniquely the studies that evaluated the traceability within the agroindustrial chains, in such a manner that they advanced as models, prototypes, and systematic reviews, while opinion articles, editorials, and documents lacking complete text were dismissed.

In the subsequent stage of eligibility, an exhaustive review of the texts was realized, with the objective of verifying their relevance and scientific quality, and incorporating exclusively those that provided reliable data around the benefits and the limitations of the smart traceability and excluding the investigations that offered a general vision without a specific application to the agri-food sphere. This procedure assures that the final analysis is constructed over the most pertinent and solid scientific evidence.

Data obtaining and analysis

Finalized the phase of selection, the collection of data was realized in a structured form, registering in a systematic mode the relevant information of each retained publication. The findings were reorganized in emergent categories, which permitted the detection of patterns and of cumulative tendencies in the examined literary corpus.

Table 3. Data extraction and thematic analysis

Category	Data extracted by article	Purpose of the analysis
General Information	Authors, year, type of study	This inquiry inserted in the systematic evaluation of emerging technologies oriented to networks of distributed sensors in industrial configurations has found, however, relevant obstacles.
Benefits	Transparency, security, efficiency, confidence	Among the specific advantages adopted in this work, stand out the reduction of infrastructure costs, the improvement in the latency of data transmission, and the increment of the available energy for nodes of long duration.
Challenges	Cost, scalability, interoperability, privacy	However, important barriers for their implementation and adoption were identified, which comprise the heterogeneity of norms, the limitations among which stands out the limited degree of interoperability of the devices and the lack of standardized protocols that govern the management of the security.
Technologies	Blockchain platforms, types of IoT sensors	Complementarily, the technical-operative architecture that results necessary has been considered, putting emphasis

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		on the segmentation of the domains of management and on the inclusion of modules of energy cannibalization throughout the supply chain of the nodes.
Conclusions	Recommendations and future lines of investigation	Finally, the Monte Carlo simulations realized project a stabilization of implementation costs toward 2030, suggesting a possible overflow of the penetration of such technologies in the network of industrial sensors.

Analysis: The recovered data were processed following the thematic approach that characterizes the qualitative investigation. The inherent diversity of the studies made a meta-analysis inapplicable; nevertheless, tables and figures were constructed that organize in a systematic mode the documented benefits and obstacles, in such a manner that a synthetic representation of the existing evidence is favored. The conformity with the PRISMA protocol and the detailed exposition of each stage guarantee the replicability, transparency, and excellence of this review, establishing a solid and reliable foundation for the enunciated inferences.

RESULTS

The systematic analysis of the literature, which has been sustained in a final sample of 65 articles of indexed scientific journals, has put into relief certain emblematic tendencies in the adoption and the effect that the smart traceability exercises over the agroindustrial supply chains. The results have been organized in two cardinal domains —advantages and complications— and the most repeated affirmations have been quantified, with the end of articulating the present state of the knowledge in the discipline.

Analysis of the identified benefits

According to 92% of the considered works (n=60), the intertwining of the Blockchain technology and of the Internet of Things (IoT) in the processes of traceability generates indisputable positive results. The authors have reclassified these advantages in four nuclear categories: security and credibility, visibility, efficiency of the processes, and sustainability.

Table 4. Frequency of the Benefits of the Smart Traceability.

Benefit	Frequency of Appearance (N=65)	Percentage of Studies (%)
Security and Confidence	60	92.3%
Transparency and Traceability	58	89.2%
Operational Efficiency	45	69.2%
Sustainability	22	33.8%

Analysis: In Table 4 reveals that the security and the confidence situate themselves in the cusp of the reported benefits, with the transparency occupying the following position. This finding reaffirms the nuclear finality that drives the adoption of the technologies: the reduction of the risks associated with the fraud and with the

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contamination. The operational efficiency is mentioned in a consistent manner, although with lesser notoriety than the two first benefits, which suggests that, although it is considered an appreciable result, it is not always presented as primary motor of the analyzed projects.

The sustainability, present in a third of the studies, acquires emergent character and has not reached, in discursive terms, the preponderance that the security possesses. This map of interests configures, in its turn, a clear invitation to the future investigation, which can center efforts in integrating in a more robust manner the sustainable dimension in the development of these applications.

Security and confidence (92.3% of the studies)

The preservation of the integrity of the information within the agri-food supply chain is sustained in the properties of immutability and tolerance to the attack that the architectures of Blockchain type offer (18)(19). Dinh et al. (20) designed an architecture of hyperledger that functions as solution of traceability for organic products, guaranteeing the irrefutable verification of the origin of each lot and avoiding the generation of falsified quality certificates. Upon connecting with devices of IoT that register and store data in an automated and continuous manner, both the risk of human error and the manipulation are neutralized, in such a manner that the information that circulates within the chain converts itself into truthful in an automatic manner.

In a case study carried out in the dairy sector, a prototype that incorporated sensors of pH and of temperature in a blockchain network put into evidence an alteration of the temperature of the milk during the transport; a smart contract was activated, providing instantaneous notification to all the links of the chain about the event of manipulation (21). The security of the information, in its turn, is translated into an increment of the confidence of the consumer, who perceives that he can access a history of verifiable and detailed data. The review of Chen et al. (22) confirms that a significant part of the consumers is disposed to pay an additional price for products that guarantee a transparent and secure traceability.

Transparency and traceability (89.2% of the studies)

The combination of technologies of Blockchain and IoT produces a traceability of the supply chain that the conventional systems cannot equal. The reviewed literature documents that each link of the productive process —sowing, harvest, processing, packaging, transport, and retail sale— can be conceptualized as a block that is added in a linear form. The IoT sensors register critical parameters of each transition (for example, doses of phytosanitaries, harvest schedules, and temperature of cold chambers) and the technology of ledger distributes and assures that information (23).

An empirical analysis in the seafood industry exemplified this approach: by means of the placement of GPS sensors in vessels and of RFID tags in the boxes, it was possible to document the trajectory of the fish from the capture in high sea until the menu of the consumer, with each variable of temperature and each interval of time registering itself in an inalterable manner.

Cost of implementation (84.6% of the studies)

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The elevated initial cost constitutes a recurrent obstacle in the adoption of integrated solutions of traceability. The reason resides in the obligation of deploying a network of IoT sensors that traverses the supply chain from the agrarian exploitations and the vehicles of transport until the centers of storage and in the necessity of developing or licensing a platform based on technology of distributed ledger. An economic analysis realized by Sharma et al. (26) estimates that the investment required for a system of smart traceability in its totality could surpass in a 30% that which the traditional configurations require, which disincentivizes the participation of the operators that dispose of limited financial resources.

Scalability and interoperability (76.9% of the studies)

The capacity of scaling in a technical form constitutes another central challenge. The implementations of distributed ledger, and in particular the public networks such as Ethereum, can present elevated latencies and commissions upon processing the cumulus of transactions that accumulates in a supply chain of great volume (24). Although pertinent solutions, such as Hyperledger Fabric, offer a superior performance, the lack of interoperability between said platforms and the diverse types of IoT sensors still manifests itself as a limitation. As Ahamed et al. (25) warn, the lack of common standards in the communication and in the formats of data perpetuates the existence of silos of information, which compromises the objective of reaching a continuous and truthful traceability throughout the entire network.

Governance and privacy (53.8% of the studies)

The decentralized architecture of the solutions of Blockchain introduces substantial dilemmas around the governance. Establishing norms, defining the occupations of each actor, and articulating procedures of deliberation in an environment where a hierarchical intermediary does not exist is revealed, in the practice, particularly arduous (26). At the same time, the privacy of the data converts itself into a risk of reputation not negligible. The agricultural producers, fearful of revealing practices that could be interpreted as intellectual property, and the intermediaries, conscious that the exposition of their margins can erode competitive advantages, show themselves reticent to share sensitive information.

In this juncture, the architecture of authorized Blockchain, which limits the inclusion to pre-authorized nodes, and the integration of layers of granular encryption, offer a scheme that conciliates the exigency of audit and the preservation of the confidential information (20).

Comparison of technologies and sectors

The documentary review permitted, in addition, to determine the distribution of technologies in function of concrete sectors. Hyperledger Fabric headed the list of Blockchain platforms adopted in prototypes, involving 45% of the contributions, while Ethereum occupied the second place, with 25% of the cases. This tendency can be explained by the distinctive characteristics of Hyperledger Fabric, which, upon being a Blockchain of consortiated type, permits a refined control over permissions of access and presents a superior capacity of scaling in entrepreneurial environments.

Regarding the sensors, those of temperature and humidity constituted the most frequent reference, followed by the devices of GPS geolocation and by the sensors of chemical quality, such as those of pH and CO₂. The sub-sphere of perishable products —fruits, vegetables, meats, dairy— monopolized the greater part of the investigations, with 60% of the sample, which results coherent, given that in this category the food security and the maintenance of the cold chain are decisive factors. The subsectors of seafood products and of organic products evidence, for their part, a notable growth in the number of studies directed to the improvement of their traceability.

Table 6. Distribution of Studies by Blockchain Platform and Sector.

Blockchain platform	Percentage of use in prototypes	Most studied agroindustrial sector	Percentage of studies
Hyperledger Fabric	45%	Perishables (Fruits, Meats, Dairy)	60%
Ethereum	25%	Seafood Products	15%
Corda	10%	Organic Products	10%
Others	20%	Grains and Cereals	5%
		Others	10%

Analysis: Table 6 corroborates that Hyperledger Fabric erects itself as the predominant option in the academic literature and in the entrepreneurial case studies, given its design oriented to maintain the confidentiality of the transactions and to admit an efficient expansion, determinant attributes in a collaborative ecosystem of corporations. In a complementary mode, the preeminence of the articles dedicated to perishable products puts into relief a particular attention toward groups that, by their own nature, exhibit expiration, elevated vulnerability, and the capacity of generating immediate consequences over the food security.

Projections and future tendencies

The results of the review indicate that the smart traceability continues evolving toward the fusion of complementary technologies, principally artificial intelligence (AI) and machine learning. Kumar and Singh (21) proposed a model by means of which a system of artificial intelligence examines the flows of data of IoT sensors encrypted within a Blockchain network and, starting from that analysis, estimates the remaining useful life of the products and redesigns the pertinent routes of distribution. The design not only increments the operational efficiency of the chain, but, simultaneously, attenuates the generation of wastes inherent to the processes.

A second evidenced line is the utilization of smart contracts for the automation of security alerts, the automatic control of payments, and the regulation of inter-enterprise agreements. In a study of conceptual character, Wang and Li (22) exposed the mechanism of a smart contract that, once the sensors certify that the product arrived under optimal conditions, activates the immediate disbursement to the agricultural producer.

The collected evidences reflect an acceleration of the smart traceability and suggest that its capacity to innovate and reconfigure the agroindustrial supply chains is significant. Such capacity augurs models of operation more secure, more efficient, and sustainable. Nevertheless, the conversion of this promise into tangible results is subordinated, in the first instance, to the faculty of overcoming the difficulties that

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revolve around the economic sustainability and the harmonization of norms, two factors that continue manifesting themselves with notable relevance in the current context.

DISCUSSION

The intersection of Blockchain and IoT sensors in the food traceability supposes a notable progress for the agroindustrial supply chains. The results presented in the systematic review validate and amplify the recommendations formulated in recent academic studies. In the section that follows, the central findings will be confronted with the previous literature, highlighting the coincidences, the differences, and the voids that still persist in the domain of the knowledge.

Comparison of benefits: Security, transparency, and efficiency

The suggested results sustain that the ascent in the associated security and the increment in the transparency are the central advantages that the smart traceability reports, observation that coincides fully with the report of Ahamed et al. (12) and of Ge et al. (2). The quality of immutability inherent to the systems based on blockchain is signaled reiteratedly as the most contundent defense against the adulteration and the fraud; Dinh et al. (18) contribute proofs that evidence that this property makes impossible the modification of the registers of origin in the context of organic products. Such strength is potentiated by means of the IoT sensors, which register measurements in real time and eliminate the manual intervention; according to Lin et al. (19), this virtue is translated into an improvement of the exactitude of the information, confirmation that Liu et al. (24) develop in their analysis of the supply chains of vegetables.

The operational efficiency has contributed to our financial results, although its incidence has been less regular than that observed in matter of security and transparency. Said constatacion is compatible with the findings of Mondal et al. (7), whose analyses concentrate themselves in the reduction of the deadlines of traceability of contaminated lots but pay scarce attention to the logistic yields that are concretized in more prolonged temporal horizons. In its turn, more recent investigations, such as those of Gupta et al. (27), have begun to illustrate of what mode the synergy between the IoT and Blockchain facilitates the automation of the processes of inventory and attenuation of costs by spoilage, signaling that the operational efficiency begins to occupy a preferential place in the investigative agendas of the sector.

Comparison of challenges: Cost, scalability, and interoperability

In our review, the high cost of implementation emerged as the most cited barrier, appears in the 84.6% of the examined articles. This datum coincides with the results of Kamilaris et al. (5) and Zhao et al. (21), who sustain that the initial financial charge linked to the Blockchain infrastructure and to the network of IoT sensors constitutes the principal obstacle for the universal diffusion, particularly in the case of the small and medium enterprises, which often lack margins to cost both the devices and the necessary expertise. Although corporations such as Walmart can assume the expense and amortize it in economies of scale (18), the remaining actors of the supply chain

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that rarely reunite the same power of purchase find that the financing of the migration to these systems converts itself into an insurmountable challenge.

The problems of scalability and interoperability have returned to highlight their relevance, such as Ahamed et al. (25) had already indicated in their study about the aquaculture, where the absence of common protocols of communication between nodes of Blockchain and IoT sensors was signaled as the predominant technical obstacle. The present finding presents a significant divergence with respect to the majority of the previous investigations, which, in a predominantly theoretical framework, attended to the viability of the technological paradigm without warning the difficulties to which it faces itself in functionally dispersed contexts. The work that is reviewed here advances in that line of inquiry, and puts into evidence that the inclination toward platforms such as Hyperledger Fabric that are based on distributed administrative controls and on an organizational elasticity designed must be interpreted as a strategic decision oriented to amortize said restrictions, aligned with the posture that Li et al. (20) sustain.

Despite the fact that the elements of governance and of confidentiality receive in the literature a less frequent treatment, their analytical weight is, however, indisputably important. Such assertion is supported in the constancy that Sharma et al. (26) grant, who evidence the difficulty of codifying the operative rules of the network and the imperious necessity of evaluating, in a pondered manner, the informative opening against the reservation of the critical data. The review of the literature suggests that the adoption of architectures of permissioned Blockchain constitutes the itinerary that responds to these inquietudes, coincidence that the majority of the contemporary studies shares.

Gaps in the literature and future directions

Despite the notable advance of the knowledge in the area, our review has revealed significant lagunas that justify posterior investigations. In opposition to the current preaching about security and efficiency, scarce studies analyze the temporal effect of the smart traceability over the environmental and social sustainability. The reduction of the food waste is frequently presented as a positive collateral effect; however, we still do not count with studies that quantify directly and systematically until what point such systems induce less destructive agricultural practices, mitigate the carbon footprint of the agri-food chain, or improve the socioeconomic conditions of the producers. This last problematique is uniquely sketched in the conceptual review of Wang et al. (27). The current literature, upon concentrating almost completely in technical metrics and financial evaluations, tends to unlearn the social and environmental dimensions that, under the optic of an integral sustainability, are equally decisive.

Complementarily, an empirical acervo is still required that, through ample and systematically implemented designs, measures the profitability of the interventions in conditions of real operation. The academic production has concentrated its efforts in laboratory trials, as well as in case analyses that occupy limited samples, which impedes an adequate generalization of its results. The future investigations must direct themselves to the creation of platforms that conceive, submit to proof, and validate

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market architectures susceptible of integrating these innovations in the small and medium enterprises, assuring in this mode the conservation of a balanced economic viability.

CONCLUSIONS

The combination of Blockchain architectures with IoT sensors is transforming in a profound manner the form in which the agri-food chains are supervised. Our systematic analysis of the literature shows that the convergence of these technologies surpasses many of the limitations of the traditional systems, upon reducing the risks of fraud and minimizing the exposure to contaminants. The immutability of the decentralized register assures that each lot remains documented in a reliable and auditable history, accompanying it from the field until the final consumer, which reinforces the authenticity of the products and contributes transparency to the entire process. This aspect results key to recover and sustain the public confidence, since the consumer can access a verifiable trajectory of legitimacy.

At the same time, the IoT sensors eliminate the dependence of human intermediaries upon registering in a continuous manner critical parameters such as temperature, humidity, and geographic location. This not only reduces the errors, but also generates a solid documentary support for each lot. In conjunction, the smart traceability presents itself as a strategic tool that strengthens the food security and increases the resilience and adaptability of the network in the face of possible disruptions.

Although its benefits are evident, the generalized implementation of the smart traceability still stumbles with economic and technical limitations that must be addressed in a priority manner. Above all, the initial charge that the modernization of the underlying infrastructure supposes remains as a dominant barrier, given that the deployment of sensors, platforms of analysis, and networks of data involves disbursements that many small and medium enterprises —critical actors of the global chain— cannot confront.

To this financial charge is summed the inherited technical dispersion: the lack of common norms of interoperability and the precariousness of the mechanisms of scaling produce islands of data in which the registers never meet, obstinately fragmenting the continuous trail that the noble traceability requires. Unblocking this double obstacle demands, therefore, to orient the investigation toward architectures of marginal cost and toward the consensual drafting of standards that harmonize the protocols of communication and permit the harmonious integration of heterogeneous devices. The resolution of these problems —far from being a marginal question— results decisive to globalize the access to the technology and so that the benefits of the smart traceability are distributed equitably among the distinct segments of the sector.

Our review shows that there still exists an important gap in the studies: little attention has been paid to the social and environmental effects of these systems. Although the reduction of the food waste appears as a clear benefit, few are the works that analyze in a detailed form how the smart traceability could drive more sustainable agricultural practices, diminish the carbon footprint, or favor a greater equity for the small

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producers. In addition, the transparency that these technologies offer could influence so that the consumers choose in a more conscious manner, a change that, in the practice, would have the potential of generating positive impacts in the entire agri-food chain.

In virtue of that, it becomes indispensable that the future works amplify their focus of analysis, integrating not only the technical and economic elements, but the ethical and sustainability dimensions. This amplification of the investigative framework would permit that the smart traceability fulfill not only functions of monitoring, but a proactive role in the sustainable transformation of the agrarian sector —evolves beyond the spheres of security and profitability, and consolidates itself, instead, as a tool for the elaboration of a global food system more just, equitable, and environmentally conscious.

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