RESEARCH ARTICLE

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Is Blockchain a Panacea for Guarding PDO Supply Chains? Exploring Vulnerabilities, Critical Control Points, and Blockchain feasibility in Greece

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Within food Supply Chains (SCs), food products labeled through Geographical Indications (GIs) hold paramount importance as distinctive and culturally significant entities, ensuring the integrity and distinctiveness of regional specialties. By strictly regulating the geographic origin and production methods, the Protected Designation of Origin (PDO) not only guarantees the preservation of traditional practices but also safeguards the cultural legacy and identity of the regions where genuine PDO products are produced. However, the very mechanisms safeguarding PDO authenticity can be exploited within globalized food systems, creating opportunities for fraudulent activities and intentional or unintentional adulteration. This study specifically delves into the overarching realm of PDO SCs, using PDO Feta cheese as a prominent case study. Through an assessment of Feta cheese SC in Greece, encompassing the Delphi Technique with the amalgamation of the design stages of Hazard Analysis and Critical Control Points (HACCP), Vulnerabilities Assessment and Critical Control Point (VACCP), and Threat Assessment and Critical Control Point (TACCP) methodologies, the operations, vulnerabilities, and critical control points are scrutinized. The results indicate multifaceted vulnerabilities and Critical Control Points (CCPs) in the Feta cheese SC that need to be addressed and constitute a precursor for augmenting PDO SCs. Moreover, the utilization of Blockchain Technology (BT) exhibits intrinsic potential for enhancing the administration of supply chains with the potential to fundamentally transform data management practices and foster increased levels of trust among stakeholders.

1. Introduction

The safeguarding of Geographical Indication (GI) products holds paramount significance in ensuring the integrity and distinctiveness of regional specialties. These products, deeply rooted in the cultural and geographical identity of specific regions, carry a unique heritage and reputation that should be preserved. Within the GI system, the Protected Designation of Origin (PDO) scheme guarantees the strongest links to the place in which products are made.[1] The PDO designation not only underscores the unique qualities of these regional specialties but also elevates their economic value and market desirability.[2] Therefore, the preservation of the authenticity and integrity of PDO products is a matter of cultural heritage, economic sustainability, and rural area development. However, the path to preserving the distinctiveness of PDO products is fraught with challenges within Food Supply Chains (FSCs), regarding the implemented practices, management, and governance. The intricacies of these challenges span various dimensions, including issues of traceability, transparency, and efficiency.[3]

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The complexities arise at each stage of the Supply Chain (SC), from the sourcing of raw materials to the final product, reaching consumers. Authentication of origin, prevention of adulteration, and maintenance of quality standards required for PDO certification become intricate tasks in a globalized environment.[4] These challenges pose a tangible threat to the credibility and reliability of PDO products, warranting a meticulous examination of the vulnerabilities and critical control points intrinsic to the SC.

At the crux of addressing the challenges faced by PDO SCs lies the pivotal role of agricultural systems. These systems serve as the foundational bedrock upon which the entire PDO SC is built.[5] The agricultural practices employed in the production of PDO products are not only integral to their unique characteristics but also significantly impact the socio-economic layers of local communities.[6] Sustainable and resilient agricultural systems not only ensure the consistently high quality of raw materials but also contribute to the longevity and viability of local economies.[7,8] Thus, recognizing the interconnectedness of agricultural practices with the overall integrity of PDO SCs becomes imperative.[9] Emerging technologies, such as Blockchain Technology (BT), have been identified as effective solutions for augmenting the traceability and ensuring the integrity of GIs. For instance, BT can contribute to maintaining the identity of the genetic variety of food products along the chain.[10,11] Therefore, it can be crucial in preserving the integrity of PDO food products that bring significant value. The utilization of BT, characterized by its decentralized and immutable ledger system, presents a novel approach to tackle challenges pertaining to transparency and trust within the SCs.[12] Blockchain guarantees a transparent and auditable record of the complete journey of each product by documenting every stage of SC, ranging from milk sourcing to final packaging, on an immutable digital ledger. This feature not only facilitates the ability of producers and authorities to monitor the origin of each product but also grants consumers an exceptional level of transparency regarding the authenticity of the product.[13] Subsequently, the detection of any form of adulteration or fraudulent activity is promptly achievable due to the inherent transparency of the Blockchain system, which exposes any anomalies within its data.[14] The utilization of this technology, in conjunction with other technologies, such as IoT sensors for environmental monitoring and RFID tags for individual product tracking, holds the promise of strengthening the supply chains certified by GIs against deceptive activities while concurrently enhancing consumer trust.[15] Although BT presents a key opportunity to be applied in GI SCs to guarantee and strengthen the integrity and traceability of the food products and processes characteristics, it is challenging to adopt and apply it withinSC practices and across stakeholder arrangements.[16] For this reason, it is crucial to expand the understanding of barriers and triggering factors that can hinder, or encourage, the adoption and the applicability of BT technologies in GI SCs. Building on this research problem, this paper aims at improving knowledge through empirical and operational findings on vulnerability factors and related potential solutions regarding the adoption and applicability of BT within GIs supply chains, based on the specific PDO scheme of the Feta cheese SC, in Greece. It should be stated that this paper strongly considers the internal mechanisms and procedures of manufacturing/processing and retail companies through the embodiment of the design phases of Hazard Analysis and Critical Control Points (HACCP), Vulnerabilities Assessment and Critical Control Point (VACCP), and Threat Assessment and Critical Control Point (TACCP) protocols in its methodological core. This has arisen as a missing point from the existing literature, as a recent review reveals.[10]

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The next chapter illustrates the general problem of preserving GIs integrity and how this is tackled through the analysis of vulnerability points in the Feta PDO in Greece. Chapter 3 presents the methodological approach and the dataset developed through a mixed methodology that combines HAACP, VACCP, TACCP, and an expert consultation Delphi technique. In Chapter 4 the results are presented, while the discussion follows suit in Chapter 5 in light of the existing literature.

2. Exploring the Problem of Preserving GIs Integrity: The Case of the Feta PDO in Greece

Feta cheese, a distinctive and culturally significant dairy product, has garnered significant attention in the fields of gastronomy, nutrition, and food science. Originating from Greece, Feta cheese has evolved into an internationally acclaimed dairy commodity recognized for its unique sensory attributes and nutritional composition. It has historical roots in ancient Greece, spanning over thousands of years. Feta cheese holds a distinguished position in both the Greek and worldwide markets, being widely recognized as the most renowned Greek cheese, whilst having the highest export sales ranking.[17] In addition, feta cheese has been granted the status of a PDO product inside the European Union since 2002,[18] adhering to specific criteria pertaining to name, provenance of raw materials, inherent attributes, delineation of production techniques, demarcation of the geographical region of origin and production, provisions for inspection frameworks, and precise specifications for labeling.[19] This PDO status not only preserves the traditional methods but also safeguards the integrity of the product, while its SC embodies this tradition, highlighting the importance of geographical origin and production methodology in crafting a product of distinct quality and characteristics. Given the fact that PDO Feta cheese has a unique cultural and gastronomical importance and can be found in worldwide markets, it was selected as a PDO representative for further assessment in this study. The production of PDO Feta cheese necessitates the utilization of sheep's milk exclusively, or a combination of sheep's milk and up to 30% goat's milk, within designated regions of Greece (geographical area of mainland Greece and the department of Lesvos – **Figure 1**).[20] Its distinct tangy flavor, crumbly texture, and characteristic saltiness make it a

Figure 1. Designated regions of Greece for Feta cheese production.

unique sensory entity within the cheese universe, warranting exploration from both scientific and gastronomic perspectives.[21]

The PDO Feta cheese SC assumes profound importance within the broader context of dairy production and regional identity. This specialized supply chain exemplifies the rigorous attention and commitment to traditional practices in the creation of a product that possesses exceptional quality and specific characteristics. By strictly regulating the geographic origin and production methods, the PDO designation not only guarantees the preservation of traditional practices but also plays a crucial role in safeguarding the cultural legacy and identity of the regions where genuine Feta cheese is produced.[22] This, in turn, supports local economies and rural communities by promoting the continued cultivation of indigenous ingredients and the employment of traditional cheesemaking expertise. Furthermore, the PDO Feta cheese SC guarantees consumers a product of unparalleled quality and consistency, as it is subject to rigorous quality controls and inspections.[23] In an era marked by globalization and homogenization of food products, the PDO designation stands as a beacon of authenticity, anchoring Feta cheese to its historical and geographical roots, while recognizing the significance of terroir in culinary traditions and preserving cultural heritage for future generations.[24]

In notable juxtaposition to the meticulously regulated PDO Feta cheese SC, the landscape of dairy production has, on occasion, been susceptible to the prevalent issue of food fraud. Food fraud is a concerning occurrence in which unscrupulous individuals may partake in deceitful activities, such as adulteration or mislabeling of products, with the aim of maximizing financial gains while disregarding the health and safety of consumers and legitimate producers.[25] Within the dairy sector, instances of counterfeit Feta cheese or similar PDO products falsely labeled have surfaced, undermining the integrity of this cheese variety.[26] These fraudulent practices not only undermine the authenticity and quality of Feta cheese but also erode consumer trust and distort market dynamics.[27,28] The PDO designation, characterized by rigorous regulations and traceability measures, presents a strong contrast to these deceptive practices, thereby highlighting the significance of preserving the authenticity of traditional food products in a time marked by growing intricacies and obstacles within the FSC.

This research examines the intricacies of the PDO Feta cheese SC, utilizing rigorous methods to identify weaknesses and enhance the integrity of this dairy product. Furthermore, this study analyzes the PDO Feta cheese SC of the "Olympos – Hellenic Diaries SA" producer and "Masoutis S.A." retailer, both situated in Greece. The primary emphasis is placed on analyzing the operational aspects and technological advancements employed within this particular SC. The operations, vulnerabilities, and critical control points—which include both accidental and intentional risks—are examined through an assessment that combines the Delphi Technique with the design stages of the HACCP, VACCP, and TACCP methodologies. Furthermore, the application of BT, characterized by its decentralized and immutable ledger system, demonstrates inherent capabilities for enhancing the management of SCs. More specifically, the potential impact of using BT within the PDO Feta cheese SC is significant, as it has the capacity to bring about fundamental changes in data management procedures and enhance trust levels among the various players involved.

3. Experimental Section

3.1. Methodology Formation

The methodology employed in this study exemplifies a comprehensive and rigorous approach to comprehensively assess the multifaceted challenges posed by food safety and authenticity within PDO SCs. Recognizing the critical importance of safeguarding the integrity of PDO products, a blend of established frameworks and expert consensus is utilized. The utilization of these approaches is grounded in the pre-implementation phase of any system, with the purpose of establishing a framework of guidelines for the implementation of BT. At its core, to ensure the depth and accuracy of the assessment, the Delphi Technique is employed, leveraging the collective knowledge of a panel of experts in the fields of food safety, supply chain management, and food authenticity. To strengthen this approach, the design stages of a triad of methodologies were utilized: HACCP to address unintentional hazards, while simultaneously integrating the design stages of VACCP and TACCP methodologies to scrutinize potential vulnerabilities and threats, both intentional and unintentional. The design phases of these methodologies have been selected due to their high importance for food safety, and managerial, and operational impact from an enterprise viewpoint. Moreover, the amalgamation of these methods facilitates a comprehensive assessment of potential hazards and provides a set of actionable directives aimed at fortifying the PDO SCs against diverse perils, thereby ensuring the safety and authenticity of PDO products.

To elaborate more, the methodology employed for gathering the information needed about PDO SCs is based on the Delphi Technique. The Delphi technique is a method utilized to collect and synthesize knowledge and viewpoints from a cohort of

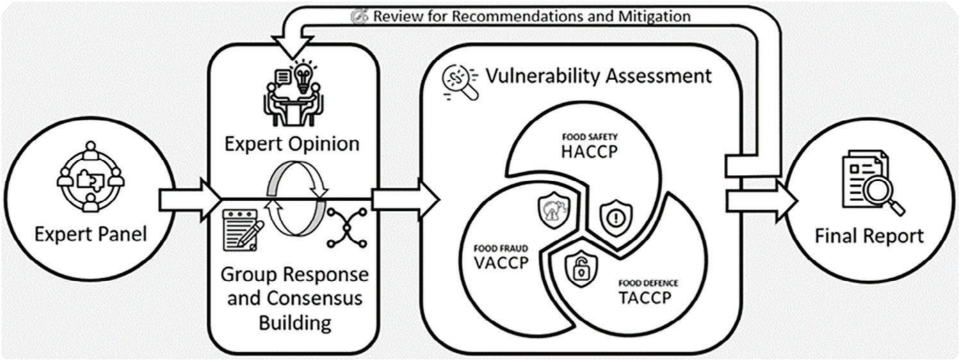

Figure 2. Vulnerability assessment of PDO SCs methodology: Delphi, HACCP, VACCP, and TACCP.

experts or stakeholders with the aim of making well-informed decisions or forecasts.[29] The initial development of this method can be attributed to the RAND Corporation during the 1950s, wherein it served as a systematic and anonymous means to elicit expert viewpoints.[30] The principal objective of the Delphi technique is to attain consensus or convergence of viewpoints among the participants.[31] The purpose of employing an iterative method in this study is to achieve a consensus regarding the challenges and weaknesses encountered in the Feta cheese SC of "Olympos – Hellenic Diaries SA" producer and "Masoutis S.A." retailer. The Delphi technique involves initiating a preliminary survey administered to a cohort of participants or experts, followed by a number of iterative rounds of discussion among the members of the group, which are directed by a designated facilitator responsible for overseeing the feedback process.[30] Following each round, participants are requested to rigorously reassess the aspects and opinions presented by the cluster during the preceding iteration. This procedure is likely to be iterated several times until a consensus is ultimately achieved. Typically, a consensus is achieved over a series of two to four iterations.[32]

In conjunction with the Delphi Technique, this study employs the design stages of a triad of methodologies to comprehensively assess the safety, security, and integrity of PDO SCs, specifically the one of PDO Feta cheese. The first approach entails HACCP, which can provide a structured framework to identify and mitigate unintentional hazards that could compromise the safety of PDO SCs.[33] By assessing biological, chemical, and physical hazards at Critical Control Points (CCPs), the primary focus is placed on maintaining the utmost level of food safety throughout the entirety of the production and distribution procedures. In the context of the second method, VACCP is utilized to delve deeper into the analysis of potential vulnerabilities and risks of food fraud and intentional adulteration.[34] It is used to identify vulnerabilities in the SC, such as ingredient substitution or mislabeling, which could undermine the authenticity of PDO SCs. Turning to the third methodology, TACCP is applied to gain additional insights into the deliberate threats that could disrupt the SC.[35] This includes acts of sabotage, product tampering, or intentional contamination. By evaluating CCPs for security breaches and assessing their potential impact, TACCP contributes to a more comprehensive understanding of the security risks inherent in the SC. Altogether, the amalgamation of the design phases of these three methods, HACCP, VACCP, and TACCP, forms a robust foundation for scrutinizing the safety, authenticity, and security of PDO SCs. This ensures that the multifaceted challenges encountered in the SCs are thoroughly assessed. The combination of these methods, along with the Delphi Technique, is visualized in **Figure 2**.

3.2. Methodology Implementation

As shown in **Figure 3**, the steps formulated to perform the analysis of this study are as follows:

3.2.1. Selection of Experts

A panel of 90 experts and stakeholders with expertise in food safety, food security and authenticity, supply chain management, and related fields was initially identified. These stakeholders included representatives and employees from the "Olympos – Hellenic Diaries SA" producer and the "Masoutis S.A" retailer, as well as other experts from the field. This selection was crucial for obtaining insights into the intricacies of the PDO Feta cheese SCs and associated risks.

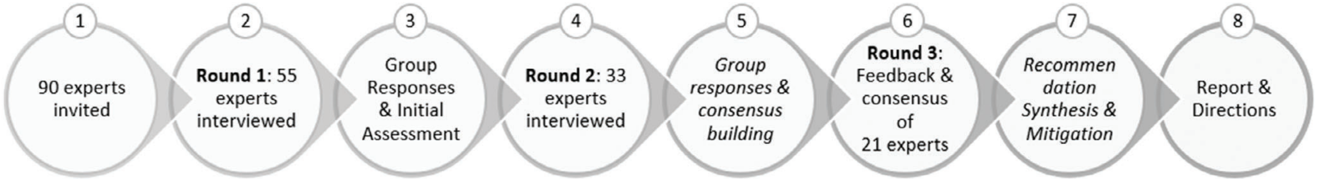

Figure 3. Methodology implementation steps.

3.2.2. Delphi Technique Iteration – Expert Interviews

Following the selection of the expert panel, expert interviews were conducted to delve deeper into the intricacies of the Feta cheese SC. These interviews are of paramount significance in the collection of qualitative data and the acquisition of expert viewpoints on various aspects of the supply chain, such as its structure, processes, and employed technologies. In the first stage, the data collection process commenced with fully anonymizing the information of the stakeholders to elicit unbiased and candid responses. Invitations were extended to 90 stakeholders, and their responses were sought. A total of 55 stakeholders accepted the invitation and participated in the initial round of expert interviews. This process was facilitated by administering surveys and questionnaires to the experts, which encompassed:

1) *Mapping the Feta Cheese Supply Chain*: The viewpoints of experts were gathered regarding the SC's end-to-end processes, encompassing all stages from the farm to retail sales. Detailed insights were sought to delineate the various stages, actors involved, logistical intricacies, and flow of raw materials and finished products.
2) *Technological Ecosystem*: An overview of the technologies and systems integrated into the supply chain was provided by experts, including information on tracking and tracing technologies, data management tools, and quality control mechanisms.
3) *Identification of Vulnerabilities*: Through targeted questions and further conversation, experts shared their insights on potential vulnerabilities within the SC. Their expertise highlighted areas susceptible to food fraud, mislabeling, adulteration, and other risks.
4) *Critical Control Points*: Experts were consulted to pinpoint critical control points where interventions, monitoring, and risk mitigation measures might be most effective. Their inputs contributed to a more nuanced understanding of where safeguards were most required. To elaborate, the processes of Steps 2 and 3 (as shown in Figure 3) are repeated multiple times until a consensus is reached.

3.2.3. Delphi Technique Iteration – Group Responses and Initial Assessment

Following the expert interviews, the collected data and responses underwent a process of grouping. This step was pivotal in gathering a collective expert perspective on the intricacies of the Feta cheese SC, its associated vulnerabilities, and CCPs. In addition, it involves the compilation of summaries for the preliminary HACCP, VACCP, and TACCP analyses. The utilization of the HACCP approach is intended to identify and mitigate unintentional hazards in the Feta cheese SC. This includes biological, chemical, and physical hazards that could compromise the safety of PDO feta cheese. This analysis is extended to encompass VACCP, which focuses on potential vulnerabilities and risks related to food fraud and intentional adulteration, such as ingredient substitution, mislabeling, or tampering that could affect the authenticity of PDO Feta cheese. By incorporating TACCP into the methodology to assess deliberate threats that could disrupt the feta cheese SC, acts of sabotage are considered. This includes product tampering or intentional contamination.

3.2.4. Delphi Technique Iteration – Reiteration – Expert Recommendations and Feedback

Subsequent to the initial consensus-building phase, a crucial step of reiteration and refinement was undertaken to solidify expert recommendations and directives. The utilization of this iterative process facilitated a thorough review and improvement of the consensus. This round involved fewer participants in the expert panel than the initial one. Specifically, 33 experts participated in this round of the Delphi Technique.

3.2.5. Delphi Technique Iteration – Group Responses and Consensus Building

Following the expert recommendations, the feedback collected was integrated during the process of consensus building.

3.2.6. Delphi Technique Iteration – Reiteration – Feedback and Consensus

As part of this step, summaries of the HACCP, VACCP, and TACCP analyses are given to the experts. They are then asked to give their thoughts on how accurate and thorough the assessments were when it comes to accidental risks, weaknesses, and planned threats. In addition, the summaries undergo revisions to include the input and insights provided by the experts. This iteration involved a reduced number of participants, with a total of 21 experts.

3.2.7. Delphi Technique – Recommendations' Synthesis and Mitigation

The feedback and input provided by the expert panel are collated and integrated into the analyses of HACCP, VACCP, and TACCP. This process enhances the comprehensiveness and credibility of the assessment, covering unintentional hazards, vulnerabilities, and intentional threats.

3.2.8. Delphi Technique – Report and Directions

This step includes the development of the final report and recommendations based on the amalgamated study that incorporates expert insights from HACCP, VACCP, TACCP, and the Delphi Technique. This step aims to present a thorough analysis of the hazards, vulnerabilities, threats, crucial control points, and mitigation measures associated with both inadvertent and intentional risks. These recommendations will be used as directions for the Blockchain development within the ALLIANCE project.[36]

4. Feta Cheese Supply Chain and Technological Ecosystem

At the core of this study pertaining to the safety, security, and authenticity of PDO Feta cheese lies a comprehensive exploration

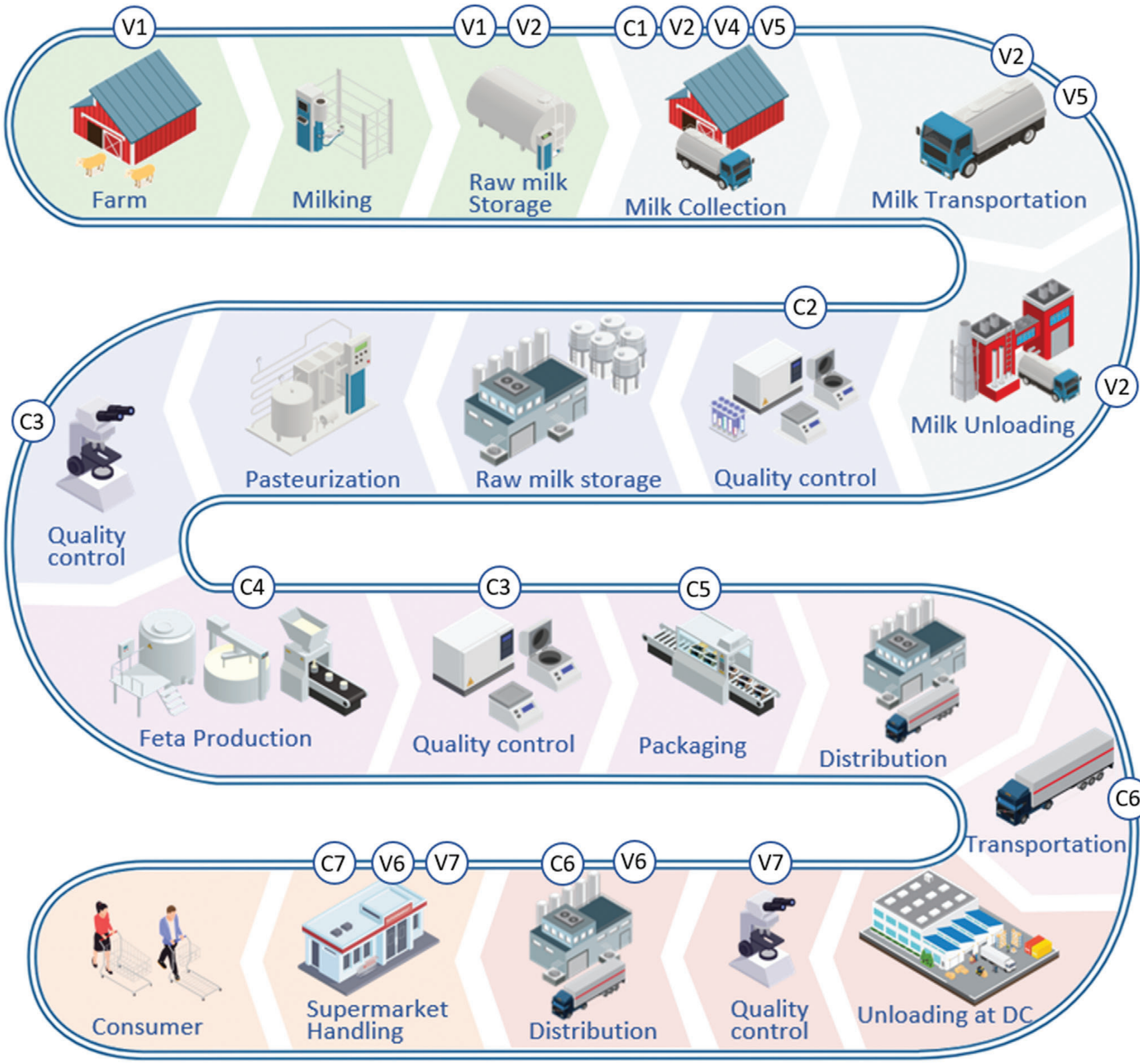

Figure 4. Feta cheese SC of "Olympos" producer and "Masoutis" retailer – V, Vulnerability; C, Critical Control Point.

of the SC of "Olympos" producer and "Masoutis" retailer and the technological ecosystem that underpins it. The supply chain of PDO Feta cheese spans from the sheep and goat farms to the retail stores, weaving a complex tapestry of processes and actors. It is within this intricate web that the integrity of PDO Feta cheese is both nurtured and challenged. This section explores the several stages of the PDO Feta Cheese SC, providing insights into its internal operations, logistics, and the crucial role of technology in guaranteeing quality, traceability, and safety. This analysis delves into the tools, processes, and technologies that have played a crucial role in the modernization of Feta cheese manufacturing and distribution.

4.1. Feta Cheese Supply Chain of "Olympos" Producer and "Masoutis" Retailer

To begin with, the steps of the PDO Feta cheese food supply chain of "Olympos" producer and "Masoutis" retailer from farm to retail store and the final consumer are outlined below. These steps are also depicted in **Figure 4**:

4.1.1. Milk Production

The supply chain begins with farmers, who raise sheep and/or goats to produce milk. PDO Feta cheese must be made from milk sourced within the designated geographical area. The milk produced is stored in specialized iceboxes provided by Olympos, which indicate the storage temperature.

4.1.2. Milk Collection

The milk collection has three phases: the collection from the producer, the transportation, and the unloading to the main facilities.

1) Prior to the milk collection from the producer, the pH and temperature of the milk stored in the icebox are checked, and a sample is taken. In addition, the results of the measurements along with the information associated with the collection are recorded in the ERP system of "Olympos" by the truck driver, and a receipt is issued.
2) Milk is collected from multiple farms and transported to a dairy processing facility. The transportation procedure encompasses the monitoring of temperature and location along the journey from the farms to the main facilities.
3) Upon the arrival of the truck at the facilities, the milk is subjected to a quality control process to verify and validate its quality characteristics before being unloaded into the silos. Indicatively, the characteristics that are analyzed are pH, composition, % water, % cow's milk, and % sheep and goat milk. The collected milk may undergo mixing; however, it is imperative that it originates only from the PDO geographical region. Both the journey and quality report data are recorded in "Olympos" ERP.

4.1.3. Milk Pasteurization

The milk is pasteurized to eliminate harmful bacteria and pathogens while preserving its flavor and texture. This procedure is implemented in order to guarantee the safety of the milk. Subsequently, the pasteurized milk is subjected to a quality control process to verify and validate its quality characteristics. These data are recorded in the ERP system of "Olympos."

4.1.4. Feta Cheese Production

The process of PDO Feta cheese production involves the procedures of culturing and coagulation, curd cutting, stirring, cooking, draining, salting, molding, and aging. Quality control checks are conducted both before and after production, and the reports are recorded in the ERP system of the "Olympos."

4.1.5. Feta Cheese Packaging

Once the cheese has aged to the desired level, it is removed from the aging facility and subsequently packaged and labeled for distribution. Afterward, the product is stored in the refrigerators of the "Olympos" cold storage warehouse.

4.1.6. Feta Cheese Distribution to the Retailer

The packaged PDO Feta cheese is transported to the Distribution Centers (DC) of the "Masoutis" retailer. The temperature of the trucks is monitored during distribution to preserve quality, and the data are recorded in the "Olympos" ERP system.

4.1.7. Feta Cheese Unloading at the Distribution Center

The packaged PDO Feta cheese is visually inspected along with temperature measurements. In addition, random sample quality control checks are performed. These data are recorded in the "Masoutis" ERP system while the products are stored in the cold storage warehouse.

4.1.8. Feta Cheese Distribution to the Final Retail Stores

The product is transported to "Masoutis" final retail stores (supermarkets). The temperature of the trucks is monitored during distribution to preserve quality, and the data are recorded in the "Masoutis" ERP system.

4.1.9. Supermarket Handling

PDO Feta cheese is made available to consumers through the supermarket "Masoutis". On supermarket arrival, the packaged PDO Feta cheese is visually inspected along with temperature measurements. In addition, random sample quality control checks are performed. These data are recorded in the "Masoutis" ERP system while the products are stored either in the in-store fridges or storage fridges.

4.1.10. Consumer Purchase

Consumers purchase PDO Feta cheese for personal or professional use.

4.2. Technological Ecosystem of "Olympos" Producer and "Masoutis" Retailer

Olympos' milk transporters receive the milk by recording the data with a portable Personal Digital Assistant (PDA). These PDAs have preinstalled software that can be used offline, even in areas without Internet access. In addition, they have 4G access in order to send the data to their ERP system. Furthermore, the milk is transferred by trucks that have temperature and location control. Each truck has a GPS that transmits its location data to the cloud, while the data captured are represented on a map. Using this tool is imperative, as it can be verified whether the route of the truck is within the correct bounds. In addition, the milk is stored in iceboxes, and each icebox displays the temperature.

In Olympos facilities, there are devices that measure the quality and possible adulteration of milk. Namely, Milkoscan, Combifoss, and Foodscan are used for the chemical composition.[37] Batcoscan and MOCON are used for the possible growth of pathogenic microorganisms, while a cryoscope is used to identify possible water adulteration. Each device utilizes its own database and is able to export the results. They also have interface software to facilitate the import of the data into their main ERP system.

The current infrastructure of Masoutis retailers consists of logistics, IoT sensors, ICT systems, and facilities. Specifically:

Table 1. Main vulnerabilities reported by the experts in the PDO Feta cheese FSC of "Olympos" producer and "Masoutis" retailer.

Vulnerability	Assessment	Actor	Importance
V1. Low educational level – lack of digitalization literacy	HACCP	Milk Producer	Low
V2. Low level of automation processes (manual data entries)	HACCP, VACCP	Milk Transp.	High
V3. Authenticity control based on sampling	VACCP, TACCP	Milk Transp.	Mid
V4. Low level of internet connectivity in rural areas in the collection	HACCP, VACCP	Milk Transp.	Low
V5. Low level of connectivity between the PDA software and GPS telematics	VACCP, TACCP	Milk Transp.	Low
V6. Scattered data and information generated through product distribution	VACCP	Retailer	Mid
V7. Lack of digitalized critical information in retail	HACCP, VACCP	Retailer	High
V8. A centralized ERP system controlled by one entity	VACCP	Producer & Retailer	High

- There is a Warehouse Management System (WMS) system for the logistics center that communicates with different databases where information related to the product is stored (quantity, expiration date, date of receiving, location where it is stored in the warehouse, and date of delivery to each store). Data is imported into the system either by using a computer through automated processes, interfaces, or wireless scanners.
- Sensors for 24-h temperature monitoring in all compartments of the logistics center are utilized. A building management system is also used, while its database is not connected with the ones for the WMS system.
- Trucks are equipped with temperature sensors to monitor their refrigeration system.
- Temperature sensors fare installed in the majority of Masoutis' stores to monitor the temperature of freezers and refrigerators continuously.
- An ERP-like system is applied to the stores, but it lacks the same level of accuracy and depth as the ones implemented in the warehouse.

5. Findings

The focal point of this study centers on the comprehensive assessment of vulnerabilities and CCPs within the Feta cheese SC. The assessment considers various stakeholders and processes along the supply chain, examining key vulnerabilities and proposing control measures to alleviate these risks. This assessment is based on the Delphi Technique, complemented by the design phases of the three methodologies: HACCP, VACCP, and TACCP. The vulnerabilities and CCPs identified and agreed on in the final round of the Delphi Technique, that can be resolved in the context of the ALLIANCE project toward Blockchain implementation, are described in this section.

5.1. Vulnerabilities and Weaknesses in the Feta Cheese Supply Chain

The vulnerabilities identified and agreed on in the final round of the Delphi Technique, that can be resolved in the context of the ALLIANCE project toward Blockchain implementation, are quoted in **Table 1**. Also, they are visualized in Figure 4.

At the forefront of the identified weaknesses is the fact that small ruminant breeders appear to have low digital literacy and show resistance to any change that could alter their typical procedures. This inertia in the digital transformation of the FSC concerns mostly Olympos' associate milk producers, who are not familiar with the utilization of digital technologies. The lack of digital literacy among many of these producers poses a significant challenge. Their resistance to adopting digital technologies hinders the seamless integration of their operations into the digital Feta cheese SC. Applying the HACCP methodology, it is identified that the educational level and digital literacy of milk producers are critical factors affecting the safety and authenticity of PDO Feta cheese, as this inertia in digital transformation can result in data inaccuracies and inefficiencies.

Shifting the focus to the associate milk transporter, the consensus concluded that there is a low level of automation during the milk collection and transportation processes. The reliability of data recorded during the transportation of milk from producers to Olympos' facilities is a critical concern. Manual data entry processes introduce the risk of errors and inaccuracies, particularly regarding temperature data and pH, which are vital for ensuring product safety. By employing VACCP and HACCP, the vulnerability in the authenticity control process based on sampling is identified. In the event of measurement values that are not acceptable, the truck driver could deliberately manipulate the data that is input into the ERP system. Likewise, it is possible for the employee to inadvertently submit inaccurate data.

Tied closely to the previous weakness, another aspect that requires attention is the fact that there is no control over the reliability of the samples received. Samples are taken both from the cooling tanks (iceboxes) and from the truck's compartment, but the information given by the driver and producers (external partners) cannot be ensured to be reliable. Authenticity control based on sampling is a common practice, but it introduces vulnerabilities related to the reliability of samples and the information provided by external partners. By employing VACCP and TACCP, a vulnerability in the authenticity control process based on sampling is identified. For instance, the truck driver has the ability to alter the samples obtained from each producer, driven by economic or behavioral incentives. This could potentially lead to misrepresentations of the quality and authenticity of the milk.

Adding to the list of concerns is a significant weakness associated with the low level of internet connectivity in rural areas where milk is collected. This vulnerability relates to the BT, as in each stage the data uploaded to the Blockchain are timestamped. Thus, the limited internet connectivity in the rural areas where milk is collected by Olympos' associate transporters can cause inaccuracies in future implementation. In many rural and isolated areas, the accessibility and dependability of internet connectivity sometimes exhibit inconsistencies. In addition, this limitation in connectivity can impede the real-time transmission of critical data, including milk collection information, to central systems. As a result, there may be delays in updating essential SC data, potentially impacting decision-making, traceability, and overall SC efficiency. By applying VACCP and HACCP, this weakness leads to a deficiency in uploading the data to the ERP system. Thus, any kind of manipulation can occur.

Beyond the already-discussed weaknesses, attention must be given to the current system's interoperability. Olympos utilizes telematics to monitor truck routing. However, the process of receiving the milk and the GPS system are not interconnected. The lack of seamless integration between PDA software and GPS telematics poses interoperability challenges. Real-time monitoring of milk transportation is crucial for data accuracy and control, as Feta cheese is a PDO product with restrictions regarding the origin of raw milk. By utilizing VACCP and TACCP, this weakness was identified, as the truck driver could exploit this lack of cross-connection.

When looking at the weaknesses through a different lens, the distinct challenge posed by scattered data and information generated through product distribution cannot be overlooked. Scattered data generated throughout the distribution process presents challenges in terms of compatibility and accessibility. This lack of integration hampers effective data utilization for decision-making and traceability, and with a view to Blockchain implementation, the issues of interoperability, compatibility, and accessibility are crucial. Expanding on the identified weaknesses, it is crucial to highlight that there is a lack of digitalized critical information in stores, where the products are arranged on the fridges. Data collection and recording are done manually in the final retail stores. Thus, human errors are quite frequent. The absence of digitalized critical information in stores, such as lot numbers, expiration dates, and product quality, contributes to challenges in traceability. By applying HACCP, manual data collection can increase the risk of human errors and traceability challenges. For instance, certain products may be inadvertently misplaced and stored in inadequate temperature conditions. VACCP also contributes, since human errors could be neglected, as they could lead to economic losses.

Concluding the discussion on vulnerabilities, it is essential to highlight the final point concerning the centralized nature of the ERP system, which is controlled by a single entity, in this case, the company (Olympos-producer or Masoutis-Retailer). Both companies are reliable and trustworthy, and frequent inspections by third-party organizations are performed. However, the fact that they have full control over the data cannot be ignored. Data stored in the centralized ERP system could be manipulated or tampered with by the company, potentially compromising data integrity and trustworthiness. By applying VACCP, there is a risk that the company may have the ability to manipulate or tamper with the data stored in the ERP system for various purposes, which could include financial gain, regulatory compliance, or even covering up operational issues. Such manipulation could lead to inaccurate reporting, potentially affecting supply chain transparency, traceability, and overall data reliability.

5.2. Critical Control Points of the Feta Cheese Supply Chain

Following the vulnerabilities, the CCPs identified and agreed on in the final round of the Delphi Technique that can be resolved in the context of the ALLIANCE project toward Blockchain implementation, are quoted in Figure 4 in each stage of the Feta cheese SC and given in **Table 2**:

Additional CCPs were identified in the first round of the Delphi Technique, but due to the rigorous protocols employed by the companies to monitor the feta cheese production and journey, they were deemed to have minimal risk and will not be addressed in the ALLIANCE project due to their low impact.

5.3. Potential Benefits of Blockchain for the Feta Cheese Supply Chain

The utilization of BT, which is distinguished by its decentralized and immutable ledger system, exhibits intrinsic potential for augmenting the administration of supply chains. The system functions within a decentralized network of nodes, where transactions are securely recorded and interconnected in a sequential manner, so guaranteeing both transparency and permanence of data. Within the framework of the PDO Feta cheese SC, in the final round of the Delphi Technique, the expert panel agreed that the implementation of BT has the potential to fundamentally transform the current data management practices and foster increased levels of trust among the stakeholders as all data stored will be verified from multifold parties. When we reached a consensus, we concluded that the potential advantages of BT implementation in the PDO Feta cheese SC can augment its overall transparency, and the expected outcomes are as follows:

1) *Enhanced Traceability*: Every stage of production, from milk sourcing to product distribution, can be recorded on the Blockchain, providing a transparent and immutable record of the product's journey.
2) *Improved Authenticity*: The utilization of BT enables the verification of product authenticity through the secure recording of essential information, including the origin of milk, processing specifics, and steps taken for quality control.
3) *Real-time Monitoring*: The utilization of BT facilitates real-time monitoring of temperature, location, and other pertinent data points, hence mitigating the risk of data inaccuracies.
4) *Efficient Auditing*: Auditors and regulators possess the capability to utilize the BT in order to authenticate adherence to PDO standards and quality control protocols.

6. Discussion

In this section, we delve into the multifaceted challenges and potential solutions identified through a comprehensive exploration of the supply chain dynamics and technological constraints within the context of PDO SCs. By employing a rigorous methodology involving the Delphi Technique and drawing upon insights from a diverse array of scholarly research, critical issues arise. By synthesizing findings from both primary and secondary sources, a nuanced understanding of the complexities inherent

Table 2. Major critical control points reported by the experts in the PDO Feta cheese FSC of "Olympos" producer and "Masoutis" retailer.

z	SC Stage	CCP	Description
CCP 1 (C1)	Milk Collection	Raw Milk attributes	Manual data entry during milk collection poses a risk of inaccuracies and misreporting, particularly regarding temperature data. The temperature of raw milk must be ensured to be maintained at a level that prevents the growth of harmful microorganisms. The values of pH can indicate mistorage; however, IoT sensors providing automatic data should be installed to ensure data integrity.
CCP 2 (C2)	Reception and Storage at the Cheese Manufacturing Facility	Quality Control	The quality and microbiological control is performed in a semi-automatic way during milk reception. Thus, it is susceptible to intentional or unintentional data manipulation in the system.
CCP 3 (C3)	Feta cheese production	Quality control between each stage	Feta cheese production processes are fully automated, with automatic quality and microbiological checks conducted before and after each stage. These crucial points must be verified to ensure they are functioning correctly and that the recorded data will not be altered.
CCP 4 (C4)	Maturation	Maturation Time and Temperature	Maturation is an automated process that includes various quality controls, robotic systems, and sensor data. This process spans a minimum of 3 months and requires that the stored data remains immutable. The time and temperature during the maturation phase to develop the characteristic flavor and texture of feta cheese while ensuring safety.
CCP 5 (C5)	Packaging	Packaging Integrity	While multifold inspection controls exist, the integrity of packaging to prevent contamination and maintain product quality must be ensured by third parties to increase transparency and trust in the label.
CCP 6 (C6)	Storage and Distribution	Cold Storage during Distribution	The monitoring and control of the temperature during distribution to prevent spoilage and pathogen growth must be automatically recorded.
CCP 7 (C7)	Retail and Purchase	Temperature at Retail	It must be ensured that feta cheese is stored and displayed at appropriate temperatures in retail settings using sensors that automatically record data.

in enhancing the transparency and efficiency of PDO SCs is provided, offering actionable insights for future research and industry practice. To attain consensus, a total of three iterations of the Delphi Technique were executed, wherein the number of participants decreased with each passing round. Out of the 90 experts invited, 55 accepted the invitation, 33 participated in the second round, and 21 in the final round. The decrease in participants demonstrates that this iterative process demands time and effort from participants, leading to decreased participation and a higher likelihood of not obtaining the necessary answers if an additional round is needed. This observation aligns with the literature,[32] showing that when multiple iterations are needed, there is a noticeable decrease in the number of participants.

The vulnerabilities discovered in the SC of Feta cheese by two major Greek firms align with existing research. More specifically, it was identified that most of Olympos' associate milk producers are not familiar with the utilization of digital technologies. This is a significant impediment to face in BT implementation in order to augment the transparency of PDO SCs and other studies report similar issues. A recent study reports that dairy and livestock producers in Wisconsin cannot "keep up with technology", feel "discomfort", or there is a "lack of understanding", with producers over the age of 55 considering keeping up with technology a significant obstacle to adopting technology.[38] Another study states that the main obstacles to ICT adoption are reported to be lack of digital literacy, inability to access internet connections or poor coverage, perceived lack of value for money, and perceived irrelevance of new digital technology to circumstances.[39] In another research, the authors assert that access is a significant concern, along with barriers like distrust in technology providers, limited comprehension of service terms and conditions, and apprehensions regarding sharing aggregated data with external entities.[40] In addition, another research indicates that farmers' opinions on digital technologies specifically relate to the digital ability aspect of digital inclusion, which consists of attitudes, fundamental skills, and activities, signifying that efforts are needed to comprehensively and precisely grasp this aspect of digital inclusion, which involves the implicit motivations, knowledge, and skills necessary to effectively utilize digital technologies in the sector, as well as the familial and communal factors that impact the adoption of digital technologies.[41] Moreover, in the literature,[42] it is discussed that adequate complementary education, parallel to the implementation of innovative dairy technologies, can lead to increased productivity and efficiency, complemented by a study in German dairy farms. e-Rural is a similar approach that effectively creates hyperdocuments for different literacy levels, bridging the gap between high-literacy researchers and low-literacy milk producers, and potentially improving the milk industry.[43] Ultimately, the path to successful digital integration in the milk industry necessitates a concerted effort from both industry and government to support producers with training materials and consulting services in order to enhance their digital literacy and facilitate technology adoption.

During the last round of Delphi (consensus), it was agreed that there is a low level of automation processes during milk collection (manual data entries), and the authenticity and quality attributes of the raw milk from each supplier at the source were based on samples collected in sterile containers. In other words, any mistake by the associate partner, deliberate or not, could lead to inaccurate data entry or incorrect samples. This limitation is crucial to address to enhance the transparency of PDO SCs, and other research has also identified comparable challenges.

Table 3. Potential control measures of identified vulnerabilities.

Vulnerability	Control measures
V1. Low educational level – lack of digitalization literacy	The implementation of training and support programs can enhance digital literacy among milk producers. Also, the adoption of user-friendly digital tools can streamline data entry and communication.
V2. Low level of automation processes (manual data entries)	The implementation of automated data capture processes during transportation, such as IoT sensors in the icebox, can reduce reliance on manual data entry. In addition, by utilizing BT and smart contracts, milk collection could be further automated and ensure immutability.
V3. Authenticity control based on sampling	The implementation of improved sampling protocols, including third-party verification could decrease such risk. In addition, smart samplers could be used that could track their location, and lock until milk is unloaded at the main facilities. Moreover, BT could enhance transparency and traceability in authenticity control.
V4. Low level of internet connectivity in rural areas in the collection	The feasibility of using signal boosters, mobile network extenders, or satellite connections in rural collection areas to enhance internet connectivity can be evaluated. In addition, a validation system could be developed between the truck driver's system and the producer in order to verify the data uploaded to the system.
V5. Low level of connectivity between the PDA software and GPS telematics	The implementation of an integrated system that connects PDA software with GPS telematics can enable real-time monitoring and data synchronization. The integration of these processes, in conjunction with real-time milk collection and a BT system, can enhance transparency and authenticity.
V6. Scattered data and information generated through product distribution	By implementing BT, accessibility of data across all stages of distribution could be available to the ledger, along with an increase in transparency and immutability.
V7. Lack of digitalized critical information in retail	The implementation of digital systems for recording critical information in stores, including barcoding and automated data entry can increase traceability and reduce human errors. In addition, implementing BT, along with the digitalization of the operations, has the potential to enhance the immutability and transparency of this segment of the SC, thereby strengthening confidence in the consumer.
V8. A centralized ERP system controlled by one entity	To mitigate the risk of data manipulation in a centralized ERP system, the implementation of BT can be considered. By integrating BT into the ERP system, an immutable and transparent ledger of all data transactions is created. Blockchain ensures that once data is recorded, it cannot be altered or deleted without consensus from multiple parties, enhancing data integrity.

For instance, some researchers indicate that the prevalence of automated systems on dairy farms in Ireland is exceedingly low.[44] Ireland further indicated that the collection and distribution of milk is performed by collaborating transporters with low technological infrastructure.[45] Moreover, a manual process of milk collection and milk sampling, which could be prone to human mistakes is described in another study,[46] complementing our results. In another study, it is suggested that employing efficient analysis methods and dependable technologies for process management and milk spoilage detection are essential to ensuring the quality and safety of milk products and expediting their delivery.[47] At the same time, various rapid methods, sensors, and commercial systems should be used for identifying milk spoilage and detecting microorganisms, as they offer high sensitivity, short response times, little sample preparation, compactness, and the capability for real-time monitoring of milk deterioration. Furthermore, some researchers,[48] considering the significance of milk cold storage, propose an integrated temperature monitoring system for the whole raw milk SC that can track the temperature in order to detect and decrease temperature fluctuations. Similarly, an IoT-based monitoring system for efficient milk distribution with a view to minimizing milk spoilage during milk collection and distribution is employed in a further study.[49]

The low levels of connectivity between Olympos' associate transporter and their ERP, especially the PDA software and GPS telematics, could be an issue for Blockchain implementation at a later stage. Additional constraints found in the literature pertain to the lack of interoperability. In the agricultural sector, interoperability between software or hardware platforms obliges farmers and other technology users to operate with a single enterprise, which results in decreased efficiency and additional time to conduct business. This goes without mentioning the supplementary effort and time needed to perform recurring actions, resulting in confusion and termination of platform usage.[50] Additionally, the compatibility between various networks is not guaranteed, and there is an absence of universal data standards. Facilitating active collaboration between companies with varying levels of technological maturity in terms of data collection and propagation of relevant information to end-users is likely to pose a significant challenge.[51] Furthermore, it must be acknowledged that in some regions where the raw materials are gathered, technological expertise may be limited and there may be no dependable internet connectivity.[39] In addition, farmers are required to operate with a collection of ICT tools that frequently produce data that is poorly interoperable.[52] This results in a significant challenge in consolidating farm-generated data in a manner that is both usable and trustworthy, as well as transparent, robust, and under control.

Dispersed data created during the distribution process poses difficulties in terms of compatibility and accessibility. This lack of integration impedes the proper exploitation of data for decision-making and traceability. BT has the potential to revolutionize food traceability but requires global data standards, governance, and technical solutions to fully optimize its impact on production efficiency, legal compliance, and global food security.[53] In addition, data harmonization emerges as a catalyst in the food sector for improving decision-making by aligning various data types, levels, and sources, resulting in compatible and comparable datasets for better decision-making.[54] **Table 3** summarizes the control measures to be addressed and constitutes a precursor for augmenting PDO supply chains.

Nevertheless, these vulnerabilities that are identified and the control measures proposed can be applied to the Feta cheese supply chain in Greece, which is the primary case study of this work, and vary based on the specific supply chain, vulnerabilities, and requirements. In addition, the information presented is limited to the experts' opinions, which were gathered during the Delphi Technique rounds.

7. Conclusion

This study has conducted a comprehensive exploration of the supply chain of PDO Feta cheese of Olympos and Masoutis by utilizing the Delphi technique in conjunction with HACCP, VACCP, and TACCP methodologies. The analysis of PDO Feta cheese SC revealed various vulnerabilities and CCPs that pose potential risks to the safety, quality, and authenticity of this product. These encompassed issues ranging from low digital literacy among milk producers to challenges related to data reliability, interoperability, and the centralized nature of ERP systems. Furthermore, this study explored the feasibility of integrating BT as a tool for augmenting traceability and transparency within the SC. While BT offers considerable promise in safeguarding the authenticity of PDO Feta cheese, it also brings forth challenges, including technological complexities, integration issues, and regulatory considerations. Through the process of identifying vulnerabilities and crucial control points, stakeholders are able to take proactive measures in order to limit risks and enhance the resilience of this dairy product. Furthermore, the potential adoption of BT offers a promising avenue for enhancing transparency and traceability, although its successful implementation will necessitate overcoming various challenges and increasing consumer trust.

Ultimately, this research contributes to a comprehensive understanding of the PDO SCs, providing insights into the intricate balance between tradition and innovation in the context of modern food production and distribution. The meticulous assessment of vulnerabilities and critical control points within the PDO Feta cheese supply chain, coupled with the exploration of BT's feasibility, holds promising implications for elevating consumer trust in this dairy product. It is of paramount importance to assure the locality identity of PDOs, a key feature of their premium character. The identification and mitigation of potential risks, from issues of low digital literacy among milk producers to challenges in data reliability and interoperability, reinforce the commitment to maintaining the safety, quality, and authenticity of PDO Feta cheese. This is further highlighted by the United Nation's (UN's) Sustainable Development Goals (SDGs) related to *i)* Sustainable food and agriculture (SDGs 2, 3), including food security, nutrition gap, farm-to-fork; *ii)* Cradle-to-cradle processing (SDG 12), including ecologically sustainable supply chain, more efficient and less consumptive technologies, logistics, and packaging; and *iii)* Policy and Governance (SDGs 16,17), including efficiency and effectiveness, food/energy/environmental policy, SMART (sustainable monitoring & assessment routine), and risk assessment. The proposed integration of BT emerges as a potent solution to enhance transparency and traceability, instilling confidence in consumers by offering unparalleled visibility into the product's journey from farm to table. As consumers increasingly prioritize authenticity and ethical sourcing, the implementation of blockchain, with its decentralized and tamper-proof ledger, not only safeguards against fraudulent practices but also aligns with the global shift toward more transparent and accountable food supply chains.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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