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Digital Transformation Through Traceability: Enhancing Fraud Prevention and Economic Sustainability in the Olive Oil Industry

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Abstract

Olive oil is a high-value product that is highly exposed to fraud, making robust traceability systems essential to protect authenticity, consumer trust, and competitiveness. This study examines how digital traceability technologies influence fraud mitigation and the sustainable performance of olive oil mills in southern Brazil. A systematic literature review, conducted according to the PRISMA 2020 protocol in Scopus and Web of Science, identified state-of-the-art supply chain and authentication technologies, including blockchain, IoT, RFID, QR codes, cloud computing, Big Data, artificial intelligence, and physicochemical methods. Two structured questionnaires were then applied to managers from nine mills in the main Brazilian olive oil cluster, and the data were analyzed using descriptive statistics, Chi-Square tests, and correlation measures within a framework grounded in Resource-Based View and Institutional Isomorphism theories. The results show that adoption of digital traceability is still incipient, while internal factors such as organizational commitment and marketing strategies play a more decisive role than external pressures in explaining adoption. Although managers do not yet perceive a direct impact on fraud mitigation, adoption is positively associated with economic, environmental, and social sustainability outcomes. Given the exploratory design and the small, non-probabilistic sample (n = 9), the findings should be interpreted as indicative rather than definitive. The proposed framework is intended as a transferable analytical lens that can be adapted and further validated in other agri-food and industrial contexts using larger samples and objective fraud-related indicators.

Keywords: digital transformation; traceability technologies; olive oil industry; fraud mitigation; economic sustainability; agri-food; agribusiness; agroindustry

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1. Introduction

Olive oil, extracted from *Olea europaea* L., is a premium agri-food product of high cultural and economic relevance. Its quality depends on genetic, edaphoclimatic, and processing factors, but it is also highly vulnerable to fraud and adulteration, which generate significant economic losses and undermine consumer trust [1–3]. In 2022, global olive oil production reached approximately 3.2 million metric tons, with the Mediterranean basin responsible for nearly 95% of this output, mainly in Spain, Italy, and Greece. While

Brazil contributes only about 0.1% of global production, it is the second-largest consumer worldwide, with more than 100 million liters consumed annually, surpassed only by the United States [4,5]. This paradox of low domestic supply and high demand creates both an opportunity for expansion and a challenge for competitiveness, especially given that around 75% of Brazilian olive oil production is concentrated in the southern region, encompassing more than 5900 hectares, 321 registered producers, and 22 mills [6–9].

The olive oil supply chain comprises multiple interdependent stages, from harvesting and milling to storage, transport, and commercialization. Each stage presents quality control points where failures may compromise authenticity and safety [10–13]. Traditional management practices have proven insufficient to prevent widespread cases of adulteration, counterfeiting, and mislabeling in the global market, with olive oil recognized as the second most adulterated food in the world, surpassed only by seafood [7,14–16]. Olive oil fraud typically occurs through (i) dilution/substitution with cheaper oils, (ii) misrepresentation of quality grade, (iii) false origin or certification claims, and (iv) counterfeiting of brands/packaging and documentation. Among these, substitution/dilution and grade misrepresentation are particularly harmful because they directly erode price premiums, distort competition, and undermine consumer trust. These practices threaten not only consumer health but also the economic sustainability of producers, who face costs associated with recalls, loss of reputation, and barriers to accessing international markets. From an economic perspective, food fraud imposes substantial costs across the value chain (testing, traceability compliance, recalls, litigation, reputation loss, and market-access barriers). Official monitoring reports also describe olive oil as among the most vulnerable categories within fats and oils, with recurring non-compliances linked to misrepresentation and dilution/substitution. More broadly, economically motivated adulteration is estimated to affect about 1% of global food industry revenues and has been associated with multi-billion-dollar annual losses.

Traceability systems have emerged as a fundamental response to these challenges. By ensuring the capacity to monitor products throughout the supply chain, traceability enhances transparency, accountability, and food safety [17,18]. Beyond compliance, digital traceability technologies—such as blockchain, Internet of Things (IoT), Radio Frequency Identification (RFID), big data analytics, and artificial intelligence—are increasingly recognized as strategic drivers of efficiency and competitiveness. They reduce the costs of non-compliance, enable rapid and precise recalls, optimize logistics, and open access to premium markets [19,20]. Figure 1 illustrates the stages of the olive oil supply chain and highlights where digital traceability technologies can be applied, emphasizing their contribution to fraud mitigation, cost reduction, and economic sustainability. In addition to operational benefits, digital traceability creates broader systemic impacts. It improves organizational performance, facilitates consumer confidence, and enables producers to compete in global markets, directly contributing to long-term resilience. Real-world initiatives illustrate how digital traceability can be operationalized in agri-food chains. For instance, blockchain-based traceability and tokenization projects have been reported in the banana market (e.g., Bananacoin) and in the Spanish olive oil context (e.g., Olivacoin), aiming to strengthen provenance assurance and value capture. In parallel, industry-led deployments (e.g., IBM-enabled olive oil traceability projects) demonstrate practical architectures combining digital identifiers, event recording, and shared ledgers to increase transparency and accountability. Figure 1 also summarizes these economic and sustainability benefits in an integrated perspective.

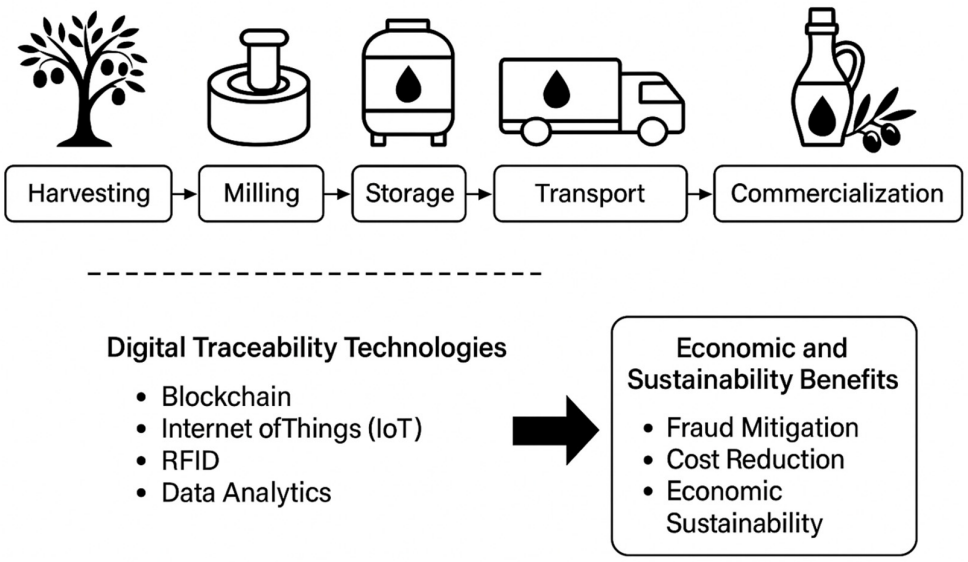


Figure 1. Integrated Olive Oil Supply Chain with Digital Traceability and Sustainability Benefits.

At the regulatory level, olive oil quality and authenticity are governed by international standards, including the Codex Alimentarius CXS 33-1981 [21], the International Olive Council (IOC) trade standards [22], and ISO 22005:2007, which provides general principles for food chain traceability [23]. These frameworks define classification, quality parameters, and traceability requirements, serving as references for national legislations worldwide. In Brazil, the Ministry of Agriculture, Livestock and Food Supply (MAPA) issued Normative Instruction No. 1/2012, which establishes definitions, classifications, and tolerance thresholds for olive oils. While aligned with Codex in the classification of extra virgin and virgin oils, the Brazilian regulation diverges by excluding the "ordinary olive oil" category and by defining oils above 2.0% acidity as lampante, unsuitable for consumption [24]. Table 1 compares the international and Brazilian regulations, highlighting convergences and divergences that reinforce the importance of digital traceability for compliance and competitiveness.

Table 1. International and Brazilian regulations.

Regulation	Scope	Key Points	Alignment/Divergence
Codex Alimentarius CXS 33-1981 [21]	International	Defines categories (extra virgin $\leq$ 0.8%, virgin $\leq$ 2.0%, ordinary $\leq$ 3.3%, lampante > 3.3%); sets hygiene and quality standards.	Reference standard used worldwide.
IOC Trade Standard (COI/T.15/NC) [22]	International	Adds *Lampante* category explicitly; details analytical methods, labeling, and trade rules.	Complement to Codex; reinforces traceability.
ISO 22005:2007 [23]	International	General principles for food and feed traceability; system design and implementation.	Framework applicable to olive oil and other sectors.
MAPA IN No. 1/2012 [24]	Brazil	Defines classifications: extra virgin $\leq$ 0.8%, virgin $\leq$ 2.0%, lampante > 2.0%; excludes the "ordinary" category; sets national rules for sampling and labeling.	Partially aligned with Codex/IOC; divergence in absence of "ordinary" and stricter lampante threshold.

Despite the growing literature on food traceability, empirical studies connecting the adoption of digital technologies to fraud prevention and sustainable performance in olive

oil supply chains remain limited. Existing contributions are mostly descriptive, with scarce integration of organizational theories to explain adoption patterns and their economic impacts. Addressing this gap, the present study investigates, from an industry perspective, how traceability technologies influence fraud mitigation and sustainable development in olive oil mills. Specifically, the objectives are to: (i) identify food traceability systems documented in the literature; (ii) map technologies currently employed by the olive oil industry; (iii) compare international practices with technologies adopted in mills; (iv) highlight potential benefits of technologies not yet explored; (v) propose a framework to assess the relationship between internal and external drivers of adoption; and (vi) evaluate, through this framework, how digital transformation supports fraud mitigation and sustainable performance.

The remainder of this paper is organized as follows. Section 2 describes the research design, including the systematic literature review, the survey instruments, and the analytical approach. Section 3 presents the findings from the literature and the empirical survey, followed by hypothesis testing and discussion. Section 4 concludes with key implications, limitations, and directions for future research.

2. Materials and Methods

In order to assess the impact of traceability technologies as a practical tool to combat fraud and to promote the sustainable development of olive oil production in southern Brazil, the methodological procedures were structured into seven stages: (i) research contextualization, (ii) systematic literature review (SLR), (iii) identification of regional traceability technologies, (iv) comparison of these technologies with the state of the art in the sector, (v) discussion of the potential benefits to be achieved in the region, (vi) proposal of a framework to evaluate the factors influencing the adoption of traceability, and (vii) assessment of the impact of traceability on fraud mitigation and the sustainable development of olive mills. The entire methodological framework is presented in Figure 2.

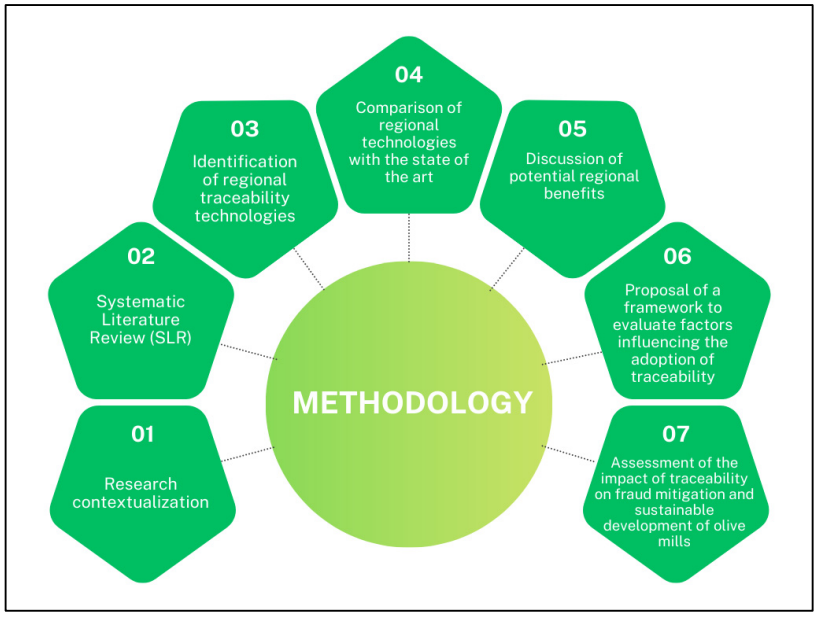


Figure 2. Methodology stages employed in the development of the article.

Each of the seven stages outlined above is provided below, with further details presented in the subsequent sections of this chapter.

2.1. Research Contextualization

The study is guided by the following research question: "From the perspective of the industry, how does the use of traceability technologies influence fraud mitigation and the sustainable development of olive mills in southern Brazil?" This question arises from the gap between the extensive international literature on food traceability and the limited evidence regarding its adoption in emerging olive oil sectors, particularly outside the Mediterranean basin. To address this gap, the study establishes the following objectives: (i) to identify food traceability systems documented in the literature; (ii) to map the technologies currently adopted by olive oil mills in southern Brazil; (iii) to compare the regional practices with international state of the art; (iv) to assess potential benefits of technologies not yet explored in the sector for fraud prevention; and (v) to propose and evaluate a framework linking internal and external factors to the adoption of traceability systems.

2.2. Systematic Literature Review (SLR)

In the first stage, a survey of the state of the art on food traceability technologies was conducted to construct the theoretical framework and to support the development of the questionnaire later applied to olive oil experts. This study followed the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [25] protocol, consulting the Scopus and Web of Science (WoS) databases.

The PRISMA methodology is widely used for the selection of relevant studies, as it standardizes the research method by detailing each stage of identification, screening, eligibility, and inclusion. This approach enhances transparency and replicability, facilitating critical evaluation of the review process [25].

For this study, a research protocol was defined and is summarized in Table 2. To improve retrieval and reduce the risk of missing relevant works, the search strategy included both direct and synonymous terms (e.g., traceability, authenticity, track-and-trace, supply chain transparency, EVOO). The time frame was initially set to 2020–2024 to focus on recent advances; however, a saturation test was performed to ensure that extending the query to 2010–2019 would not add substantially new technologies beyond those already consolidated.

Table 2. Research protocol applied.

Topic	Description
Research problem	What are the most widely used technologies currently applied to olive oil traceability?
Databases used	WoS and Scopus
Query applied	("traceab *" OR "authent *" OR "track-and-trace" OR "traceability system *" OR "supply chain transparency") AND ("olive oil" OR "EVOO")
Time frame	2010–2024 (final dataset after saturation test: 2020–2024 focus)
Document types	Peer-reviewed articles
Language	English
Inclusion criteria	I1: Articles reporting technologies for olive oil traceability (supply chain or authentication)
Exclusion criteria	E1: Articles unrelated to olive oil; E2: Studies on general industry not mentioning olive oil; E3: Articles addressing olive oil but without traceability/authentication; E4: Reviews without primary data; E5: Duplicates

The asterisk (*) is an operator that keeps the root of the word and retrieves all endings after the asterisk.

The systematic review followed the workflow illustrated in Figure 3, structured in four main stages:

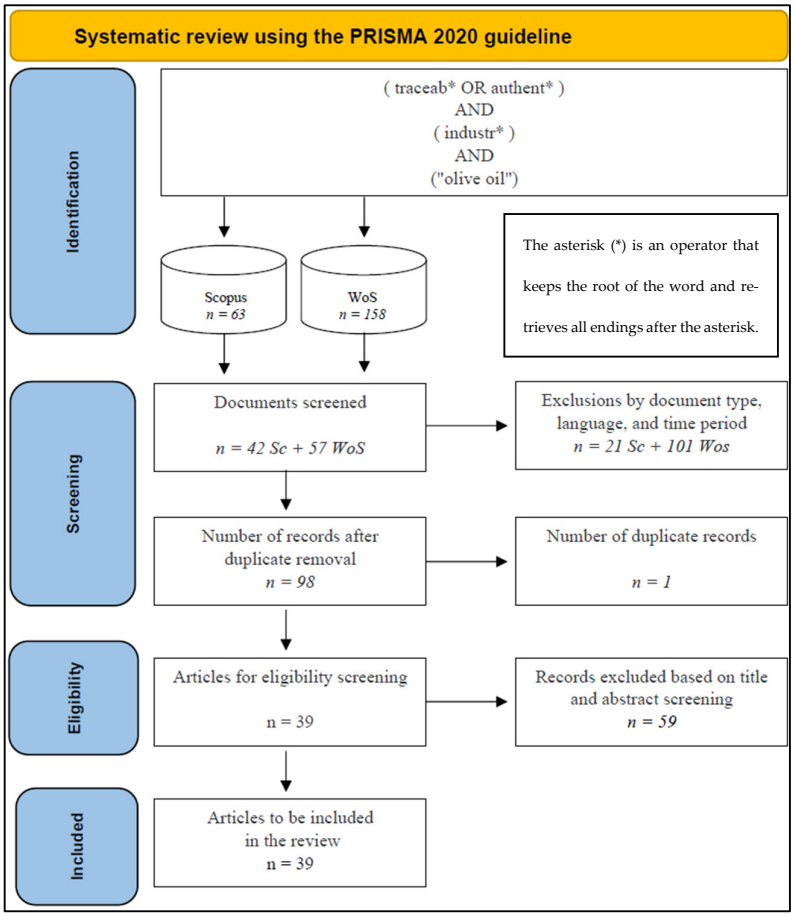


Figure 3. Systematic Literature Review using the PRISMA 2020 [25].

Identification: Database queries retrieved 63 documents from Scopus and 158 from WoS.

Screening: Filters were applied (time frame, language, type of document), resulting in 42 Scopus and 57 WoS records.

Eligibility: Duplicates were identified and removed using the bibliometrix package in R, leaving 98 unique records. Titles, keywords, and abstracts were screened against I1/E1–E5 criteria.

Inclusion: After full-text assessment, 39 articles were retained as the final dataset (Figure 3).

From the final dataset, it was possible to identify a comprehensive range of technologies that constitute the global state of the art in olive oil traceability. These findings provided the foundation for designing a questionnaire to be applied to regional stakeholders, in order to assess which technologies are currently adopted by olive mills in Southern Brazil.

The review also highlighted an important distinction: traceability technologies operate at both the supply chain level (e.g., batch-level identification through digital platforms, blockchain, or RFID) and the authentication level (e.g., analytical chemistry tools to verify product authenticity). This distinction is critical in the case of olive oil, a product highly susceptible to fraud and adulteration worldwide [26].

2.3. Identification of Regional Traceability Technologies

To map the predominant traceability technologies in southern Brazil, structured questionnaires were distributed to olive mill managers, thus initiating the data collection stage. The use of questionnaires as a data collection technique was justified not only for its efficiency in time and cost—since in-person visits to all mills would have been unfeasible—but

also because surveys are widely recognized in the literature as valid tools to capture organizational perceptions in studies on adoption of agri-food technologies [25].

Two complementary instruments were designed. The first focused on collecting demographic and structural data from mills, including location, production capacity, organizational size, and technological profile. This characterization was consistent with approaches in previous research, such as Mattevi & Jones (2016), who used similar demographic surveys to characterize small and medium-sized enterprises in the United Kingdom [20]. The second questionnaire was analytical and theory-driven, consisting of 25 statements structured into nine dimensions (Table 3). These dimensions were derived from the systematic literature review and grounded in two organizational theories: the Resource-Based View (RBV) and Institutional Isomorphism Theory (IIT). The RBV emphasizes the role of internal resources and capabilities in building sustainable competitive advantages [27,28], while IIT highlights the influence of external institutional pressures, such as regulation, consumer expectations, and industry norms, in shaping organizational practices [29,30].

Table 3. Dimensions comprising the quantitative questionnaire.

Dimension	Description	Statements	Literature
1	Government regulation *Codes: GR1 to GR4*	4	[29,30]
2	Consumer pressure *Codes: CP1 to CP3*	3	[29,30]
3	Industry competition *Codes: CI1 to CI3*	3	[29,30]
4	Optimization of production processes *Codes: OP1 and OP2*	2	[30]
5	Degree of organizational commitment *Codes: GC1 to GC4*	4	[27,28,30]
6	Marketing strategies *Codes: EM1 and EM2*	2	[27,28,30]
7	Adoption of traceability technologies *Codes: ATR1 and ATR2*	2	[30]
8	Fraud mitigation in the sector *Codes: MFS1 and MFS2*	2	[31]
9	Sustainable performance of olive mills *Codes: DSS1 to DSS3*	3	[31]

To address potential ambiguity in the term 'adoption', this study treats digital traceability adoption in two complementary ways. First, implementation is captured descriptively through the first questionnaire (i.e., which technologies are currently applied by the mill). Second, the structured questionnaire captures adoption orientation (i.e., managerial decision, readiness, and willingness to invest/expand traceability). This distinction is important in early-stage contexts where managerial intent may exist even when implementation remains limited, and it is used to interpret the evidence for fraud-related outcomes.

The nine dimensions captured both perspectives. Government regulation, consumer pressure, and industry competition (dimensions 1–3) were primarily linked to IIT [29,30]. Dimensions concerning optimization of production processes, organizational commitment, marketing strategies, and adoption of traceability technologies (dimensions 4–7) reflected RBV principles, emphasizing resource management and internal capabilities [27,28,30]. Finally, the dimensions on fraud mitigation and sustainable performance (dimensions 8–9) addressed expected outcomes of traceability adoption, aligned with the objectives of the

study [31]. A five-point Likert scale was applied to measure responses, given its versatility and ease of interpretation, as highlighted in organizational and management studies [32].

To ensure methodological rigor, a pilot test was conducted prior to full distribution, during which statements were adjusted to improve clarity and reduce ambiguities. Internal consistency of the nine dimensions was subsequently verified using Cronbach's alpha, confirming acceptable reliability for further statistical analysis. The questionnaires were administered through a mixed approach (in-person and online) between September 2024 and March 2025, maximizing response rates and accommodating managers' availability.

The research population consisted of the 22 olive mills located in southern Brazil (Figure 4). From this population, nine mills were selected through purposive non-probabilistic sampling, considering their geographic location, production capacity, and technological profile. This sampling strategy allowed representation of diverse sub-regions and organizational contexts, ranging from smaller family-run units to larger, technology-intensive producers. Although non-probabilistic, this approach was justified by the relatively small population of mills in the region and the exploratory nature of the research. It also aligns with recommendations in the literature that emphasize purposive sampling as an effective strategy when aiming to capture heterogeneity and rich insights in studies of innovation adoption [33].

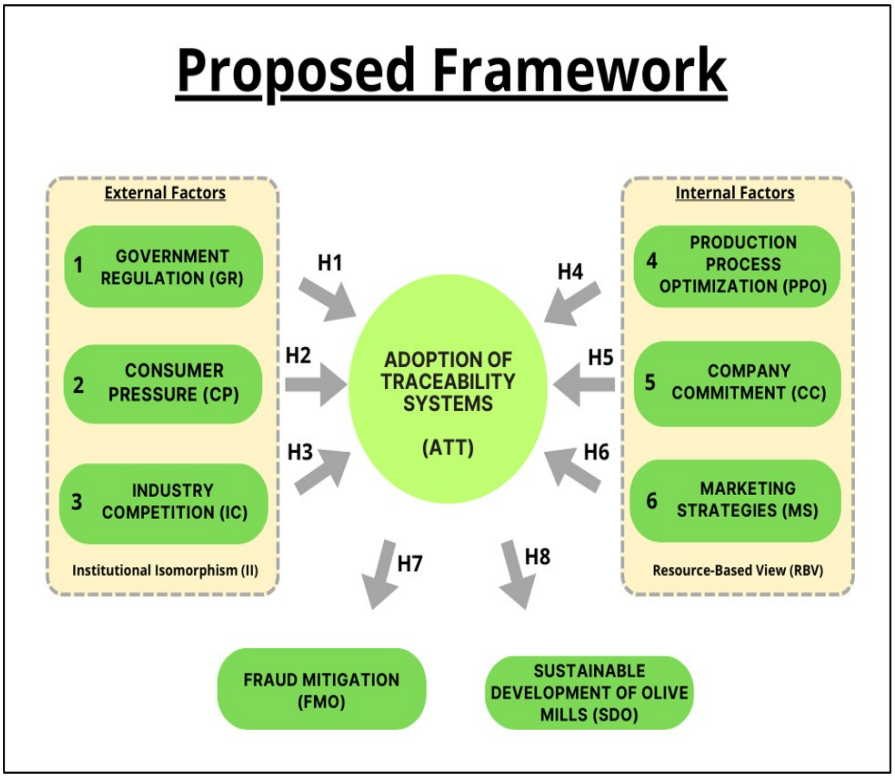


Figure 4. Framework proposal.

The proposed framework positions the Adoption of Traceability Systems (ATT) as the central construct and primary objective of the model. In this structure, external (institutional) factors—government regulation (GR), consumer pressure (CP), and industry competition (IC)—are theorized to influence ATT through hypotheses H1–H3, reflecting pressures consistent with an institutional isomorphism lens. In parallel, internal (firm-level) factors—production process optimization (PPO), company commitment (CC), and marketing strategies (MS)—are proposed as additional antecedents of ATT via hypotheses H4–H6, aligned with a resource-based view perspective. The directional logic of the arrows

therefore differs for H7 and H8: rather than representing drivers of adoption, they capture downstream outcomes enabled by achieving a robust and reliable traceability capability after managing both external and internal conditions. Accordingly, once ATT is effectively established, the model posits that traceability contributes to fraud mitigation (FMO) (H7) and to the sustainable development of olive mills (SDO) (H8), which is why these arrows point outward from the central construct. While purposive sampling does not permit broad statistical generalization, it strengthens the interpretative value of the findings by reflecting the diversity of the regional olive oil sector. This methodological design ensures that the mapping of traceability technologies provides a reliable picture of the current stage of adoption in southern Brazil and allows meaningful comparisons with the international state of the art identified in the systematic review.

In summary, this stage ensured that data collection was feasible, theoretically grounded, and methodologically rigorous. By integrating RBV and IIT, the study analyzed both internal and external drivers of traceability adoption, while the structured questionnaires enabled systematic quantification of managers' perceptions. The resulting dataset constitutes a robust foundation for subsequent analysis of the relationship between traceability, fraud mitigation, and sustainable development in olive mills.

2.4. Comparison of Regional Technologies with the State of the Art

Once data collection and sample definition were completed, the analysis stage was initiated with the objective of comparing regional practices with the international state of the art. This step sought to reveal convergences, divergences, and gaps between the technologies currently adopted in southern Brazil and those documented in the literature through the systematic review.

The comparative process involved two complementary procedures. First, the qualitative component of the questionnaire was examined using descriptive statistics, enabling the construction of a frequency distribution of the technologies cited by managers. This procedure, performed in Microsoft Excel 2021®, allowed identification of which technologies were most frequently implemented, partially adopted, or not considered at all by the regional mills. Second, the resulting dataset was systematically cross-referenced with the body of evidence extracted from the 39 articles included in the systematic literature review.

This triangulation of primary and secondary data was essential for detecting structural bottlenecks and benchmarking opportunities. For instance, technologies such as RFID, blockchain, IoT, and analytical authentication methods—widely disseminated in international experiences—were evaluated against the local scenario, where adoption remains incipient or heterogeneous. This comparison highlighted not only technological gaps but also institutional and organizational challenges that hinder the modernization of the regional sector. By aligning empirical evidence with international benchmarks, the study ensured that the proposed framework is both locally grounded and globally relevant.

2.5. Discussion of Potential Regional Benefits

The fifth stage extended the comparative analysis by focusing on the strategic benefits that could be realized if regional mills advance towards alignment with the state of the art. This stage relied heavily on the responses from the qualitative questionnaire, combined with interpretative insights from the literature.

Beyond identifying technological bottlenecks, this discussion sought to project potential trajectories for regional competitiveness. Specifically, it analyzed how the adoption of emerging traceability technologies could mitigate recurrent problems such as fraud and adulteration, while simultaneously creating value through improved logistics, certification, and access to premium markets. The discussion also considered the broader

implications for economic sustainability, including cost reductions associated with product recalls, enhanced consumer trust, and compliance with international regulations.

Furthermore, this stage provided recommendations tailored to the local context, acknowledging the sector's heterogeneity. Smaller family-operated mills, for instance, may benefit from incremental and low-cost solutions such as QR codes and digital platforms, while larger and more technology-intensive producers can accelerate the adoption of advanced systems like blockchain-based traceability and IoT-enabled monitoring. By contextualizing these strategies, the analysis not only emphasized practical feasibility but also underscored the systemic benefits for the entire supply chain.

Ultimately, this stage reinforced the argument that digital traceability technologies are not merely compliance mechanisms, but strategic enablers of modernization and sustainable development. By articulating the opportunities identified, the study provided a roadmap for regional mills to converge with international best practices, thereby enhancing their long-term competitiveness and resilience.

2.6. Proposal of a Framework to Evaluate Factors Influencing Traceability Adoption

To investigate the influence of internal and external factors on the adoption of traceability technologies by olive mills in southern Brazil, a framework was proposed based on concepts drawn from the specialized literature and grounded in the Resource-Based View (RBV) and Institutional Isomorphism Theory (IIT).

Data from the structured questionnaires constituted the empirical basis for this stage. Responses were collected on a 5-point Likert scale (−2 to +2) and analyzed using SPSS (version 22). Given the categorical and ordinal nature of the variables, non-parametric tests were applied. Associations were first tested through the Chi-Square (χ^2) test of independence, adopting a 10% significance level (90% confidence). When a significant association was detected, the strength of the relationship was subsequently measured through the Phi coefficient (φ) and Spearman's rank correlation (ρ). Non-significant results were excluded from further intensity evaluation, ensuring methodological consistency [34–37].

The hypotheses tested (Table 4) were derived from the theoretical framework. External factors—government regulation, consumer pressure, and industry competition (H1–H3)—were linked to IIT, reflecting institutional pressures that drive convergence of organizational practices [29,30]. Internal factors—production process optimization, company commitment, and marketing strategies (H4–H6)—were derived from RBV, which highlights the role of organizational resources in building competitive advantage [27,28]. Finally, the adoption of traceability technologies was tested against expected outcomes: fraud mitigation (H7) and sustainable development (H8), drawing from Zhou et al. (2021) [31].

Table 4. List of hypotheses to be investigated by the research.

Hypothesis	Relationship
H1	Government Regulation (GR) positively influences the Adoption of Traceability Technologies (ATT)
H2	Consumer Pressure (CP) positively influences the Adoption of Traceability Technologies (ATT)
H3	Industry Competition (IC) positively influences the Adoption of Traceability Technologies (ATT)
H4	Production Process Optimization (PPO) positively influences the Adoption of Traceability Technologies (ATT)
H5	The Degree of Company Commitment (CC) positively influences the Adoption of Traceability Technologies (ATT)

Table 4. *Cont.*

Hypothesis	Relationship
H6	The use of Marketing Strategies (MS) positively influences the Adoption of Traceability Technologies (ATT)
H7	The Adoption of Traceability Technologies (ATT) positively influences the Mitigation of Fraud in Olive Mills (FMO)
H8	The Adoption of Traceability Technologies (ATT) positively influences the Sustainable Development of Olive Mills (SDO)

The resulting framework is illustrated in Figure 4, inspired by Najmi et al. (2023) [30] for the structuring of internal and external factors, and by Zhou et al. (2021) [31] for the integration of sustainability outcomes. The design highlights how external institutional pressures and internal organizational capabilities interact to influence traceability adoption and its expected impacts.

2.7. Assessment of the Impact of Traceability on Fraud Mitigation and Sustainable Development in Olive Mills

The final methodological stage consisted of applying the framework to evaluate the extent to which the adoption of traceability technologies contributes to fraud mitigation and sustainable development in olive oil mills. This analysis corresponds to hypotheses H7 and H8 and operationalizes the framework developed in Stage 6.

The statistical evaluation confirmed whether adoption of traceability systems is significantly associated with (i) the reduction in fraudulent practices in the olive oil sector and (ii) improvements in the sustainable performance of mills. Using the χ^2 test, associations between adoption and outcomes were identified; φ quantified the strength of these relationships, while Spearman's ρ verified monotonic correlations between adoption levels and performance indicators.

The adoption of a 90% confidence threshold ($p < 0.10$) was justified by the exploratory nature of the study and the small population size of olive mills in southern Brazil. This choice enabled the detection of meaningful patterns while avoiding premature rejection of potentially relevant associations, consistent with methodological recommendations for exploratory research.

By linking adoption of traceability technologies to tangible outcomes—fraud mitigation and sustainable development—the assessment validated the framework as both a diagnostic tool for current practices and a strategic guide for future improvements. It demonstrated that digital traceability systems should not be understood solely as compliance mechanisms, but as strategic enablers of competitiveness and sustainability in the olive oil sector.

3. Results and Discussions

This section synthesizes the main findings from three sources of evidence: (i) the systematic literature review (SLR), which establishes the international state of the art; (ii) the regional diagnosis of adoption and barriers among olive mills in southern Brazil; and (iii) the statistical assessment of associations and hypotheses (H1–H8) linking internal/external factors, adoption of traceability technologies (ATT), and outcomes in fraud mitigation (FMO) and sustainable development (SDO). The focus is to explain what the data say and why it matters for economic sustainability and competitiveness.

3.1. Findings Derived from the Systematic Literature Review

3.1.1. Traceability Technologies at the Supply Chain Level

International evidence converges toward digital architectures that integrate identification and capture (RFID, QR, NFC), continuous monitoring (IoT, GPS), and tamper-evident registries (blockchain/cloud), supported by Big Data/AI to detect non-conformities, accelerate recalls, and document compliance [38–53]. The dominant benefits are auditable transparency, operational efficiency, and market access under increasingly strict standards. Table 5 summarizes these technologies and representative references (blockchain [42,43]; IoT and its components [44–50]; cloud [51]; Big Data [52]; AI [53]).

Table 5. Main traceability Technologies at the Supply Chain Level.

Traceability Technology	Literature
Blockchain—Ensures immutable and transparent records of every stage in the olive oil supply chain, from harvesting to commercialization.	[42,43]
Internet of Things (IoT)—Enables real-time monitoring of variables such as humidity, temperature, and storage conditions of olives and oil.	[44]
Radio Frequency Identification (RFID)—Facilitates the automatic identification of olive batches and olive oil bottles, accelerating logistics traceability.	[45,46]
QR Code—Provides consumers with immediate access to information on origin, production, and certifications of olive oil by scanning the package.	[47]
Near Field Communication (NFC)—Allows quick authentication of product provenance at the point of sale, reducing fraud and counterfeiting.	[48]
Global Positioning System (GPS)—Tracks cultivation areas and transportation routes of olive oil, ensuring geographic control of the entire chain.	[49,50]
Cloud Computing—Centralizes collected data on accessible platforms, facilitating integration among producers, distributors, and retailers.	[51]
Big Data—Analyzes large volumes of data on production, quality, and consumption of olive oil, supporting strategic decisions and anomaly detection.	[52]
Artificial Intelligence (AI)—Assists in demand forecasting, anomaly detection in production processes, and quality enhancement of olive oil	[53,54]

Operationally, 'track-and-trace' requires (a) unique identification at batch or bottle level (serialization), (b) capture of critical tracking events across harvesting, milling, storage, bottling, and distribution, and (c) data sharing and verification among supply chain actors. RFID/NFC and IoT automate event capture (location, time, environmental conditions), while cloud platforms integrate datasets. Blockchain can add tamper-evident logging of transactions and custody changes. Importantly, QR codes alone do not increase supply-chain visibility unless they are linked to a secure back-end that stores verified events, supports controlled data governance, and enables authenticity checks (e.g., tamper-evident packaging, digital signatures, and/or targeted analytical testing).

While prior studies frequently list digital traceability technologies, supply-chain security requires clarifying which technology supports which control objective and under what operational prerequisites. This is particularly relevant in early-adoption contexts, where actors may recognize technologies but still lack guidance on how to deploy them to

strengthen tracking, tracing, and anti-counterfeiting. To address this gap, we have mapped the main technologies to practical security functions, typical fraud risks, and minimum implementation requirements, as:

- Unique identification and serialization (batch/bottle) | Counterfeit bottles; relabeling; undocumented product replacement | RFID/NFC; serialized QR; tamper-evident labels; digital signatures | QR must be unique and linked to a secure back-end; labels should be tamper-evident
- Capture Critical Tracking Events (CTEs) across chain | Diversion; blending outside records; "ghost batches" | RFID gates; IoT devices; mobile apps; GPS | Define CTEs (harvest, milling, storage, bottling, shipping, receiving) and who records each event
- Integrity of records and shared ledger | Record tampering; false provenance claims | Blockchain (permissioned); secure cloud; access control | Governance rules (who writes/reads), audit trails, and data validation
- Condition monitoring and alerts | Quality degradation later "masked" as premium quality | IoT sensors (temp/humidity); analytics | Thresholds + automated alerts; link sensor data to batch IDs
- Point-of-sale/consumer verification | Counterfeit products at retail; brand misuse | NFC; QR + secure back-end; verification app | Verification must query authenticated records; QR alone $\neq$ visibility/security
- Authenticity testing (identity/purity/origin) | Dilution/substitution; misrepresentation of grade/origin | Spectroscopy, chromatography, DNA + chemometrics | Use as audit layer; best combined with chain-level traceability for enforcement

3.1.2. Traceability Technologies at Atomic Level

Complementary to chain-level traceability, authentication verifies identity, origin and purity using spectroscopy, spectrometry, chromatography, and DNA-based methods, typically enhanced by chemometric modeling [55–65]. This layer is critical in olive oil due to recurrent adulteration. Table 6 compiles the most used techniques (e.g., FTIR/FT-NIR, Raman, UV/Vis, IRMS/SNIF; GC/HPLC; SNP/SSR).

Table 6. Main spectroscopic technologies applied in analytical chemistry.

Technique	Spectral Range	Wavelength Range
Fourier Transform Infrared Spectroscopy (FTIR)	Mid and Far Infrared	2500–100,000 nm
Fourier Transform Near-Infrared Spectroscopy (FT-NIR)	Near Infrared	780–2500 nm
Raman Spectroscopy	Visible Light and Near Infrared	400–2500 nm
UV/Visible Spectroscopy	Ultraviolet and Visible Light	100–780 nm
Isotope Ratio Mass Spectrometry (IRMS/SNIF)	Radio Waves	1 mm–100 km

Additionally, Table 7 presents the common chemometric tools (PCA, PLS, SVM, DA, STOCSY, etc.).

Table 7. Chemometric tools in food authentication studies.

Technique	Author(s)	Application in the Article
Support Vector Machine (SVM)	[66]	SVM used as a basis for classification with HPLC.
Discriminant Analysis (DA)	[67]	Mid-Infrared (MIR) Spectroscopy with validation via Factorial Discriminant Analysis and Principal Component Analysis (PCA).
Total Correlation Spectroscopy (STOCSY)	[59]	STOCSY with Nuclear Magnetic Resonance (NMR) to profile the plant metabolome.
Principal Component Analysis (PCA)	[68]	Mix of Electrospray Ionization (ESI), Differential Mobility Analysis (DMA), and Mass Spectrometry (MS) validated by Principal Component Analysis (PCA) and Orthogonal Projections to Latent Structures Discriminant Analysis (OPLS-DA).
Decision Tree, KNN, and Neural Networks	[69]	Nuclear Magnetic Resonance (NMR) relaxometry validated using Machine Learning technologies (Decision Tree, KNN, SVM, Neural Networks, and Linear Discriminant Analysis).
Partial Least Squares Regression (PLS)	[58]	Near-Infrared (NIR) Spectroscopy with validation via Principal Component Analysis (PCA) and Partial Least Squares Regression (PLS).

3.2. Demographic Data and Traceability Technologies

Table 8 characterizes the nine respondents and their mills. In brief, the sample skews male (7/9), highly educated (9/9 higher education; 5/9 postgraduate), with recent sector experience (7/9 $\leq$5 years) and small scale (8/9 $\leq$25 employees; average processing ~960 kg/h). Knowledge about technologies is uneven (e.g., blockchain recalled by 4/9), while practical adoption is very low (7/9 report using none; isolated mentions of IoT, cloud, AI, Big Data, QR). The main barriers are capital (4/9) and knowledge (3/9); interest in learning and investing is high (7/9 willing to invest; 9/9 willing to deepen knowledge).

Table 8. Outcomes collected from the first questionnaire.

Question	Responses (n = 9)
Function	Master Miller (5); Owner (3); Other (1)
Highest educational attainment	Undergraduate degree (4); Postgraduate degree (5)
Experience in the mill sector	5 years or less (7); Between 6 and 11 years (1); More than 15 years (1)
Company size	25 employees or fewer (8); More than 100 employees (1)
Processing capacity of the mill	Minimum processing: 100 kg/h; Average processing: 960 kg/h; Maximum processing: 2500 kg/h
Traceability technologies known	Total unawareness (4); Blockchain (4), QR Code (3), GPS (3), Spectroscopic Technologies (2), Spectrometric Technologies (2), Chromatography (2), IoT (2), Cloud Computing (2), RFID (1), NFC (1), Artificial Intelligence (1), Big Data (1), Chemometrics (1), and DNA Markers (1)

Table 8. *Cont.*

Question	Responses (n = 9)
Traceability technologies applied in the mill	None (7); IoT (1), Cloud Computing (1), Artificial Intelligence (1), Big Data (1), and QR Code (1)
Reason for not investing in traceability	Lack of capital (4); Lack of knowledge (3); Lack of interest (2)
Willingness to deepen knowledge about traceability	Yes (9); No (0)
Predisposition to invest in traceability	Yes (7); No (2)

The regional sector displays high recognition but low implementation, typical of early digitalization stages. This gap explains the mixed statistical evidence later observed for fraud outcomes (limited variance in actual adoption) and highlights an opportunity for targeted technical assistance and financing.

3.3. Mapped Associations Among the Factors of the Proposed Framework

To assess the intensity and statistical significance of associations among the following groups—(1) internal factors, (2) external factors, (3) the decision of mill managers regarding the adoption of traceability techniques, (4) the mitigation of fraud cases in olive oil mills in southern Brazil, and (5) the sustainable development of these mills—cross-tabulation analyses were performed on the collected data. The Chi-square test was applied, and p-values were evaluated at a 90% confidence level. Whenever the p-value exceeded 0.1, independence between the variables was assumed. Conversely, when the p-value was lower than this threshold, the effect size (Phi for 2 × 2 tables or Cramér's V for larger tables) and Spearman's Rho were calculated to confirm both the significance and magnitude of associations.

3.3.1. Cross-Analysis Between External and Internal Factors

At this stage, significant associations were identified between the external factors (Government Regulation—GR, Consumer Pressure—CP, and Industry Competition—IC) and the internal factors (Production Process Optimization—PPO, Degree of Company Commitment—CC, and Marketing Strategies—MS) of the proposed framework. The set of variables concerning external factors is presented in Table 9, while Table 10 details the internal variables, their descriptions, and respective codes.

The analysis revealed, for example, that consumer-driven pressure (CP) was more influential in stimulating the adoption of traceability technologies than government regulation (GR), as demonstrated by the negative correlation between GR3 and CP1. Respondents emphasized a perceived insufficiency of regulatory incentives, suggesting that consumer demand plays a stronger role in motivating traceability adoption. Similar interpretations were drawn for associations between GR, IC, and CP, which pointed to certification and export requirements as key motivators for technology implementation in olive mills. Additional associations demonstrated that internal factors such as employee knowledge, commitment, and training (CC) are particularly relevant for supporting process optimization (PPO) and marketing strategies (MS). Conversely, not all expected associations were confirmed—for instance, GR showed no significant linkage with PPO, CC, or MS—although prior studies in the food sector suggest such relationships may exist.

Table 9. Codes and topics associated with the external variables.

Code	Topic
GR1	The existence of clear and specific government regulations for the implementation of traceability technologies contributes to the legal security of companies in the sector.
GR2	Government regulatory policies provide adequate incentives to attract investors interested in the development and implementation of traceability technologies.
GR3	Government regulations play a relevant role in promoting certifications related to traceability, aiming at quality and safety standards.
GR4	Government regulatory policies have been effective in encouraging growth and innovation within the sector.
CP1	Customer pressure for high-quality products influences the decision of organizations to adopt traceability technologies.
CP2	Export demand, with its specific requirements, motivates the adoption of traceability technologies within companies.
CP3	Customer pressure affects a company's compliance with standard market practices, particularly regarding the adoption of traceability technologies.
IC1	Fierce competition among local producers influences a company's decision to adopt traceability technologies.
IC2	Competition between locally produced and imported olive oils impacts the adoption of traceability technologies within companies.
IC3	The need for certification for export purposes influences the implementation of traceability technologies in companies.

Table 10. Codes and topics associated with the internal variables.

Code	Topic
PPO1	The optimization of production processes to meet compliance standards motivates the adoption of traceability technologies within companies.
PPO2	The growing obligation for the industry to prioritize quality management influences a company's decision to adopt traceability technologies in its production processes.
CC1	Employee commitment to food safety influences the company's decision to adopt traceability technologies.
CC2	Employee knowledge and adherence to Good Manufacturing Practices impact the company's decision to adopt traceability technologies.
CC3	Management's commitment and proactive stance towards food safety influence the company's decision to adopt traceability technologies.
CC4	Management's mobilization in providing training in the field of quality management influences the implementation of traceability technologies within the company.
MS1	The adoption of traceability technologies can be associated with the transmission of a positive image to the consumer.
MS2	The adoption of traceability technologies can be aligned with the company's marketing strategy, particularly concerning customer acquisition.

Table 11 provides a synthesis of the statistical results of the significant associations described above.

Table 11. Significant associations between External and Internal Factors *.

Association	Chi-Square	*p*-Value **	Effect Size (Phi or Cramér's V)	Spearman's ρ ***	Interpretation
GR3–CP1	15.75	0.07	1.323 (Cramér's V)	−0.45	Moderate Dependence
GR3–CP3	15.75	0.07	1.323 (Cramér's V)	0.06	Very Weak Dependence
GR1–IC3	15.60	0.07	1.317 (Cramér's V)	0.48	Moderate Dependence
GR3–IC2	19.50	0.08	1.472 (Cramér's V)	0.03	Very Weak Dependence
CP2–IC3	14.50	0.02	1.269 (Cramér's V)	0.908	Very Strong Dependence
CP3–IC1	16.37	0.05	1.349 (Cramér's V)	0.540	Strong Dependence
CP1–CC2	15.56	0.07	1.315 (Cramér's V)	0.401	Moderate Dependence
IC2–PPO1	25.50	0.06	1.680 (Cramér's V)	0.190	Weak Dependence
IC1–CC3	15.00	0.09	1.291 (Cramér's V)	0.690	Strong Dependence
PPO2–CC4	16.05	0.06	1.335 (Cramér's V)	0.816	Very Strong Dependence
CC1–MS2	13.50	0.09	1.225 (Cramér's V)	0.240	Weak Dependence
CC2–MS2	13.50	0.04	1.225 (Cramér's V)	0.480	Moderate Dependence

* Test performed for a sample of n = 9. ** Chi-Square test performed at a 90% confidence level (*p*-value $\leq$ 0.1). *** Very Weak (0–0.1), Weak (0.1–0.3), Moderate (0.3–0.5), Strong (0.5–0.8), Very Strong (>0.8).

When comparing the questions encompassed by Government Regulation (GR) and Consumer Pressure (CP), two significant associations were identified. Between GR3 and CP1, a negative correlation was observed, suggesting that consumer-driven pressure for quality and excellence stimulates the adoption of traceability technologies more strongly than governmental regulations. Respondents also expressed a lack of confidence in the ability of government incentives to attract investments, reinforcing the perception that demand-side forces play a more decisive role. A second, weaker association emerged between GR3 and CP3, again highlighting consumers as key drivers of traceability adoption in the olive oil sector of Southern Brazil [70].

In the comparison between GR and Industry Competition (IC), two significant associations were mapped. The GR1–IC3 relationship presented a moderate correlation (Spearman's coefficient: 0.48), with managers emphasizing the importance of certification for accessing international markets. This finding underscores the need for Brazilian regulations to be aligned with international standards to ensure legal security in global trade negotiations, where traceability serves as a fundamental mechanism for quality management [71]. The association between GR3 and IC2, although weaker, was also significant. Managers noted the competitive challenges posed by imported olive oils, often associated with misleading labeling or inadequate quality. In such cases, consumers tend to prioritize price over compliance, reinforcing the role of traceability as a strategic tool to safeguard consumers and disseminate institutionalized quality standards [72].

Regarding the relationship between CP and IC, two strong positive associations were observed: CP2–IC3 and CP3–IC1. The first showed very strong dependence (≈91%), underscoring the decisive role of export requirements and certification in driving adoption of traceability systems by mills in Southern Brazil. The second reflected the influence of growing consumer demand for higher quality oils, which encourages mills to adopt traceability technologies as a means of differentiation and innovation [71,73,74].

Between Production Process Optimization (PPO) and Degree of Company Commitment (CC), one very strong and positive association was identified (PPO2–CC4). This highlights that compliance with quality management standards stimulates investment in employee training, fostering a culture of continuous improvement in production systems [75].

The relationship between PPO and Marketing Strategies (MS) showed no significant associations. However, the literature suggests that process improvements—such as error

reduction, efficiency gains, or waste minimization—can later be leveraged by marketing to reinforce a positive institutional image [76].

For CC and MS, two significant positive associations emerged: CC1–MS2 (weak, 24%) and CC2–MS2 (moderate, 48%). These findings indicate that both employee commitment and knowledge of good practices influence marketing strategies, contributing to stronger consumer trust in olive oils, a product highly dependent on verified quality attributes [56].

No significant associations were observed between GR and PPO, GR and CC, or GR and MS. Nevertheless, prior studies suggest that regulations can indirectly foster standardization, commitment, and strategic marketing when linked to incentives, certifications, or penalties [77–80].

Similarly, no significant associations were found between CP and PPO or CP and MS, although the literature indicates that consumer pressure often drives firms to optimize operations and adjust marketing strategies to strengthen competitiveness [81,82].

In the relationship between CP and CC, one moderate positive association (40%) was found between CP1 and CC2, indicating that consumer pressure reinforces the need for technical expertise and adherence to Good Manufacturing Practices (GMP) among employees [81].

For IC and PPO, a weak but significant association (IC2–PPO1) was identified. Managers highlighted the need to optimize processes as a strategy to compete against imported products, which dominate lower-price segments due to fiscal advantages, while regional producers emphasize freshness and quality, often targeting premium consumers [83].

Between IC and CC, a strong positive association (IC1–CC3) was identified (69%). This indicates that competition stimulates managerial commitment to food safety, with traceability technologies recognized as central tools [84].

Finally, no significant associations were detected between IC and MS in the survey data, although the literature stresses the role of marketing in building trust and competitiveness through traceability adoption [85].

3.3.2. Cross-Analysis of External and Internal Factors with the Adoption of Traceability Technologies

This stage examined the associations between external factors (GR, CP, IC), internal factors (PPO, CC, MS), and the adoption of traceability technologies (ATT1: sustainable performance; ATT2: fraud reduction). Analyses followed the same procedure as in Section 3.3.1, with significance set at $p \leq 0.1$ and effect sizes confirmed by Phi or Spearman's Rho.

A single significant external relationship was identified—GR1–ATT1—suggesting that clear and sector-specific regulations reinforce legal security and enhance the contribution of traceability to sustainability across the environmental, economic, and social dimensions [86]. No significant links were found between external factors and ATT2, although the literature emphasizes that regulations, consumer pressure, and competition can indirectly foster fraud reduction through improved quality management [87].

Among internal factors, two strong associations stood out for ATT1—CC1–ATT1 and CC2–ATT1—indicating that employee commitment and knowledge of good practices directly promote sustainable performance [88]. For ATT2, four moderate associations were detected (CC2–ATT2, CC4–ATT2, MS1–ATT2, MS2–ATT2). These results highlight that both technical expertise and management-led training help mitigate fraud, while marketing strategies play a complementary role by informing consumers and strengthening brand reputation [56,88].

Table 12 summarizes these results, showing that internal drivers—especially organizational commitment and knowledge—are more decisive than external pressures in determining both sustainability outcomes and fraud mitigation through traceability adoption.

Table 12. Significant associations between internal and external factors and the adoption of traceability technologies *.

Association	Chi-Square	*p*-Value **	Coef. Phi	Spearman ***	Interpretation
GR1–ATT1	12.96	0.04	1.20	0.44	Moderate Dependence
CC1–ATT1	13.50	0.09	1.225	0.542	Strong Dependence
CC2–ATT1	12.00	0.06	1.155	0.570	Strong Dependence
CC2–ATT2	11.14	0.08	1.113	0.413	Moderate Dependence
CC4–ATT2	12.86	0.04	1.195	0.377	Moderate Dependence
MS1–ATT2	9.18	0.05	1.010	0.344	Moderate Dependence
MS2–ATT2	9.43	0.05	1.024	0.232	Weak Dependence

* Test performed for a sample of n = 9. ** Chi-Square test performed at a 90% confidence level (p-value $\leq$ 0.1). *** Very Weak (0–0.1), Weak (0.1–0.3), Moderate (0.3–0.5), Strong (0.5–0.8), Very Strong (>0.8).

3.3.3. Cross-Analysis of Traceability Technology Adoption with Fraud Mitigation and Sustainable Development of Olive Mills

Associations between the questions concerning the Adoption of Traceability (ATT1 and ATT2) and both the Fraud Mitigation statements (FMO1 and FMO2) and the Sustainable Performance of the mills (SDO1, SDO2, and SDO3) were also mapped, following the same methodology as the previous sections. Table 13 presents the codes and topics associated with the Fraud Mitigation and Sustainable Development of Olive Mills.

Table 13. Codes and topics associated with the Fraud Mitigation and Sustainable Development of Olive Mills.

Code	Topic
FMO1	The limitations imposed by fraud cases can impact the expansion of the entire olive oil sector.
FMO2	The need for investments in fraud combat may motivate the company to adopt traceability technologies as an integral part of strategies to protect the integrity of its products.
SDO1	The adoption of traceability technologies can play a crucial role in the industry's revenue generation, considering the transparency in the production chain and the product's valorization among consumers.
SDO2	The need to invest in traceability technologies may align with environmental preservation, considering the reduction in environmental impact throughout the productive chain.
SDO3	Traceability can promote the integration and interaction of the industry with the local community, considering transparency in practices and social responsibility.

Associations were also mapped between the items concerning Traceability Adoption (ATT1 and ATT2) and both Fraud Mitigation statements (FMO1 and FMO2) and Sustainable Performance of Olive Mills (SDO1, SDO2, and SDO3). As in the previous analyses, this stage employed a 90% confidence level, considering a p-value equal to or lower than 0.1 as the threshold for statistical significance.

Initially, regarding ATT and FMO, no significant associations were detected from the perspective of olive mill managers in southern Brazil, as the Chi-Square test yielded values greater than 0.1 in all cases. Nevertheless, the literature suggests that investments in traceability technologies may be related to the sustainable performance of olive mills and contribute to reducing fraud across the supply chain, thereby promoting the expansion of the olive oil sector in Southern Brazil at both the national and global levels [89].

The number of associations between ATT and SDO was considerably higher than those with FMO, with five out of six possible correlations identified, four of which were classified as strong. Specifically, the five positive correlations found were: ATT1–SDO1, ATT1–SDO2, ATT1–SDO3, ATT2–SDO2 and ATT2–SDO3.

In fact, the items addressed by ATT1 and ATT2, which encompass the use of traceability technologies to foster both sustainability in olive mills and fraud prevention in the supply chain, align with the SDO1, SDO2, and SDO3 items. These latter statements more specifically reflect the economic pillar (revenue generation), environmental pillar (environmental preservation), and social pillar (integration with local communities), respectively. In this sense, the associations corroborate the literature, which emphasizes the essential role of traceability in advancing sustainability practices [90].

Table 14 provides a synthesis of the statistical results of the significant associations described above.

Table 14. Significant associations between Traceability systems implementation and outcomes FMO and SDO *.

Association	Chi-Square	*p*-Value **	Coef. Phi	Spearman ***	Interpretation
ATT1–SDO1	13.80	0.08	1.238	0.390	Moderate Dependence
ATT1–SDO 2	13.80	0.08	1.238	0.730	Strong Dependence
ATT1–SDO 3	8.77	0.06	0.990	0.823	Very Strong Dependence
ATT2–SDO 2	18.00	0.02	1.414	0.756	Strong Dependence
ATT2–SDO 3	10.29	0.03	1.069	0.587	Strong Dependence

* Test performed for a sample of n = 9. ** Chi-Square test performed at a 90% confidence level (*p*-value $\leq$ 0.1). *** Very Weak (0–0.1), Weak (0.1–0.3), Moderate (0.3–0.5), Strong (0.5–0.8), Very Strong (>0.8).

3.3.4. Verification of the Proposed Hypotheses

As previously outlined, the analyses were carried out in three sequential stages, each focusing on different relationships between the constructs of the framework. The goal was to verify the hypotheses formulated in Section 2.6 and identify the main factors that influence the adoption of traceability technologies in olive mills in southern Brazil, as well as their implications for fraud mitigation and sustainable development.

Stage 1—Exploratory analysis of external and internal factors: In the first stage (Section 3.3.1), twelve significant associations were identified between External Factors (GR, CP, IC) and Internal Factors (PPO, CC, MS). Although no hypotheses were tested at this stage, the results provided important insights into the interaction between regulatory pressures, consumer demands, industry competition, process optimization, organizational commitment, and marketing strategies. These associations reinforced the role of consumer expectations and international certification requirements as central drivers, while highlighting gaps in governmental incentives and regulatory clarity. This exploratory mapping created the empirical basis for testing H1–H6 in the following stage.

Stage 2—Testing H1 to H6 (external/internal factors $\rightarrow$ adoption of traceability technologies): The second stage examined the relationships between External/Internal Factors and the Adoption of Traceability Technologies (ATT1 and ATT2), as described in Section 3.3.2. Seven significant associations were found (Table 12), allowing for the verification of hypotheses H1–H6 according to the minimum thresholds established in Table 15.

Table 15. Minimum Associations for Non-Rejection of H1 to H6.

Factor Constructs	Number of Items	ATT Items	Minimum Associations Required for Hypothesis Non-Rejection
GR	GR1, GR 2, GR 3, GR 4	ATT1, ATT2	≥4 associations (minimum of 50%)
CP	CP1, CP 2, CP 3	ATT1, ATT2	≥3 associations (minimum of 50%)
IC	IC1, IC 2, IC3	ATT1, ATT2	≥3 associations (minimum of 50%)
PPO	PPO1, PPO2	ATT1, ATT2	≥2 associations (minimum of 50%)
CC	CC1, CC2, CC3, CC4	ATT1, ATT2	≥4 associations (minimum of 50%)
MS	MS1, MS2	ATT1, ATT2	≥2 associations (minimum of 50%)

Hypotheses H1 (Government Regulation → ATT), H2 (Consumer Pressure → ATT), H3 (Industry Competition → ATT), and H4 (Process Optimization → ATT) were rejected, as the number of significant associations was below the required threshold. These results suggest that, from the perspective of mill managers, regulatory, competitive, and process-related drivers are perceived as insufficient to directly stimulate the adoption of traceability systems. In contrast, H5 (Company Commitment → ATT) and H6 (Marketing Strategies → ATT) were supported. The significant associations confirm that organizational engagement with food safety practices and the integration of traceability into marketing activities play a decisive role in promoting adoption. This indicates that adoption is more strongly influenced by internal, resource-based factors than by institutional pressures, which aligns with the Resource-Based View (RBV) perspective.

Stage 3—Testing H7 and H8 (traceability adoption → fraud mitigation and sustainability outcomes): The third stage focused on the impact of traceability adoption on fraud mitigation and sustainability outcomes (Section 3.3.3). As presented in Tables 15 and 16, five significant associations were identified between traceability adoption and sustainability indicators, but none with fraud mitigation.

Table 16. Minimum Associations for Non-Rejection of H7 and H8.

Factor Constructs	Number of Items	ATT Items	Minimum Associations Required for Hypothesis Non-Rejection
FMO	FMO1, FMO2	ATT1, ATT2	≥2 associations (minimum of 50%)
SDO	SDO1, SDO2, SDO3	ATT1, ATT2	≥3 associations (minimum of 50%)

Hypothesis H7 (Adoption of Traceability → Fraud Mitigation) was rejected, as the Chi-Square tests revealed no significant associations between ATT1/ATT2 and the fraud-related variables (FMO1, FMO2). Despite this result, the literature suggests that, indirectly, traceability can support fraud reduction by reinforcing transparency, certification, and consumer awareness. However, the absence of direct statistical evidence in the present study indicates that managers do not yet perceive these benefits in practice.

Hypothesis H8 (Adoption of Traceability → Sustainable Development) was supported, since five out of six possible associations were significant, four of them strong. Traceability adoption was shown to positively influence the economic dimension (revenue generation and product valorization—SDO1), the environmental dimension (impact reduction across the supply chain—SDO2), and the social dimension (community integration and responsibility—SDO3). These findings corroborate international evidence that highlights traceability as a cornerstone for aligning olive oil production with sustainability goals.

Overall, the hypothesis testing reveals a consistent pattern:

- Institutional pressures (GR, CP, IC) were not sufficient to explain adoption (H1–H3 rejected).

- Process optimization (PPO) also did not reach significance (H4 rejected).
- Internal organizational factors (CC, MS) were decisive (H5–H6 supported).
- Adoption did not significantly mitigate fraud (H7 rejected), but strongly advanced sustainability outcomes (H8 supported).

Figures 5 and 6 visually summarize the results, with green arrows representing supported hypotheses and red arrows indicating those rejected. Together, the findings highlight that while external forces have limited influence, internal commitment and strategic positioning are the main enablers of traceability adoption, which in turn contributes directly to sustainability rather than fraud reduction.

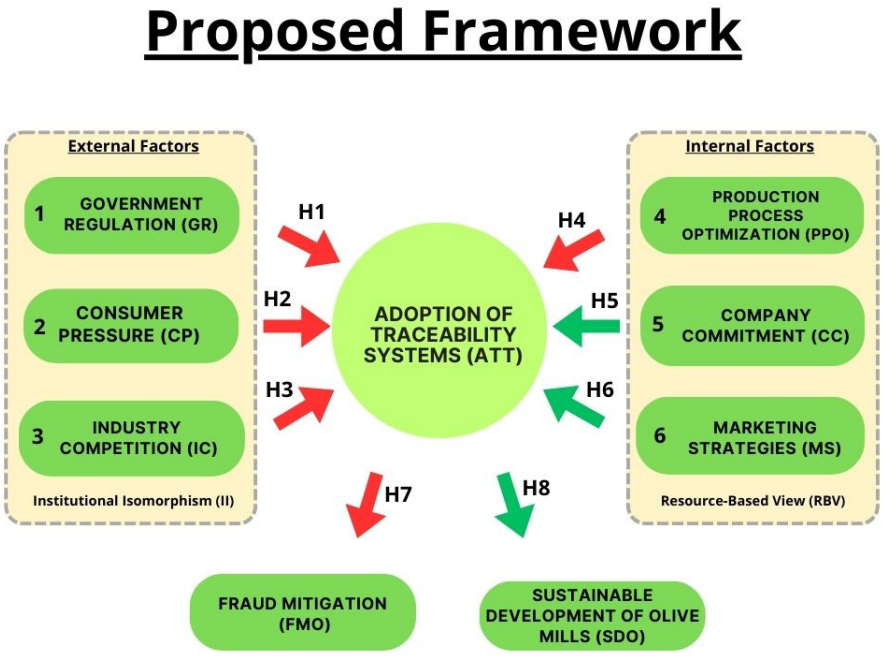


Figure 5. Hypotheses tests.

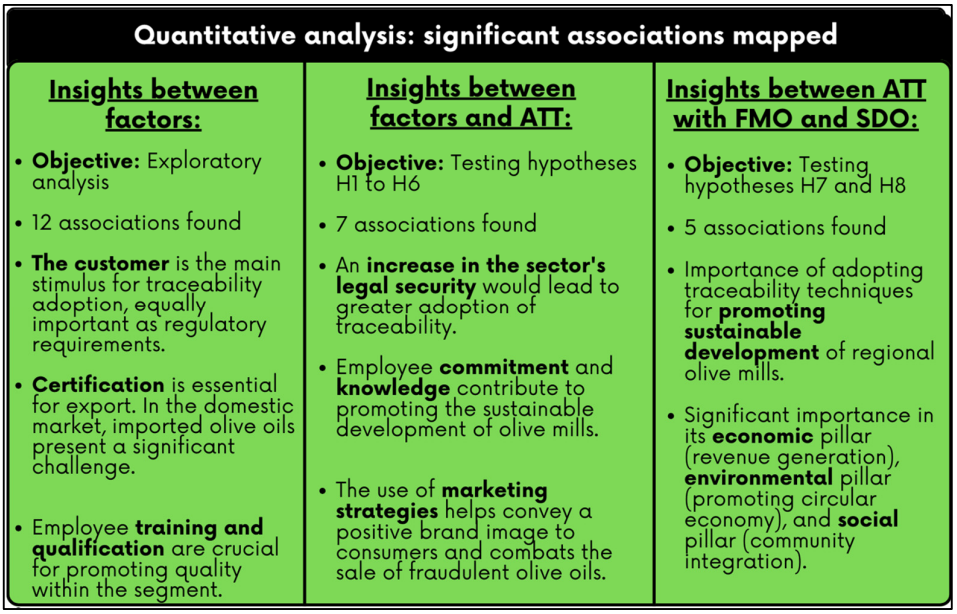


Figure 6. Synthesis of Results from the Cross-Analysis.

As presented, twelve significant associations were identified between internal and external factors. However, this first stage was exploratory in nature, and no hypotheses

were tested; the insights are reported in the previous section (Section 3.3.1). In the second stage, hypotheses H1–H6 were evaluated by examining associations between External and Internal Factors and the Adoption of Traceability Systems by olive mill managers.

For the assessment of H1–H6, Table 15 was structured to indicate the minimum number of significant associations required for hypothesis non-rejection. Accordingly, constructs GR, CP, IC, and PPO did not reach the minimum threshold in their respective relations with ATT, leading to the rejection of H1, H2, H3, and H4 (red arrows in Figure 5). Conversely, H5 and H6 were not rejected (green arrows), since CC and MS presented at least 50% significant associations with ATT.

In the third stage, associations between ATT and FMO, as well as between ATT and SDO, were examined, resulting in five significant correlations, as presented in Table 16. To test hypotheses H7 and H8, the number of significant associations between ATT–FMO and ATT–SDO was compared with the minimum threshold required for non-rejection, as shown in Table 16.

Accordingly, H7 was rejected, while H8 was not, since the Adoption of Traceability Technologies showed significant correlations in more than 50% of its relations with SDO (4 out of 6), but none with FMO (0 out of 6). H7 was not supported, which is consistent with an early-adoption setting in which most mills report no implemented digital traceability technologies and, therefore, observable anti-fraud benefits are unlikely to be visible in day-to-day operations. In addition, managers may conflate 'traceability' with 'authenticity': while traceability improves chain visibility and accountability, fraud mitigation in olive oil often requires coupling chain-level tracking with authentication controls (e.g., targeted analytical testing and enforcement). Finally, anti-fraud effects typically emerge only after broader ecosystem alignment (suppliers, distributors, retailers, regulators) and the accumulation of consistent data across critical control points, which is still incipient in the studied cluster. Therefore, the non-significant association should be interpreted as an indicative finding of limited implementation maturity rather than evidence that digital traceability cannot support fraud mitigation.

Finally, to systematize the results obtained from the cross-analysis across the three stages, Figure 6 was prepared, providing a comprehensive summary of the discussion.

4. Conclusions

The present study, entitled "Analysis of Traceability Technologies Applied to the Olive Oil Industry in Southern Brazil", addressed the guiding research question: "From the industry's perspective, how does the use of traceability technologies influence fraud mitigation and the sustainable development of olive mills in southern Brazil?". To answer this question, the research evaluated the impact of traceability technologies as a strategy for combating fraud and fostering sustainable development in the regional olive oil sector.

The systematic literature review, conducted according to the PRISMA 2020 protocol, made it possible to consolidate the state of the art in food traceability systems and to group the main technological approaches into two large categories: those oriented toward production, such as blockchain, IoT, QR codes, Big Data, Cloud Computing and Artificial Intelligence, and those based on physicochemical methods, including spectroscopic, spectrometric, chromatographic and DNA-based analyses. This mapping highlighted the technological sophistication available internationally and revealed the gap between global practices and the technologies adopted by olive mills in southern Brazil.

The field research, carried out with managers of mills located in the southern region, showed that the sector is still at an early stage of technological adoption. Although the region is recognized as the main national reference in olive oil production, the enterprises surveyed revealed limited experience, reduced processing scale, and low incorporation

of advanced traceability tools. The application of production-oriented technologies was reported only sporadically, with QR codes, IoT, Cloud Computing, Artificial Intelligence and Big Data mentioned by some managers, but without systematic integration. The results also demonstrated that lack of capital and lack of knowledge are the main barriers to adoption, while blockchain emerges as a promising alternative for the coming years, with potential to integrate the various actors in the olive oil value chain and to strengthen competitiveness in international markets.

The study also developed and tested a conceptual framework to analyze the influence of internal and external factors on the adoption of traceability systems, as well as the impacts of such adoption on fraud mitigation and sustainable development. Grounded in Resource-Based View theory and Institutional Theory, the framework enabled the evaluation of eight hypotheses through Chi-Square tests, complemented by measures of association using Phi and Spearman's Rho. The results revealed that external pressures, such as government regulation, consumer demand and inter-industry competition, did not show sufficient statistical evidence to support a direct influence on adoption. By contrast, internal factors, especially organizational commitment and marketing strategies, proved decisive, confirming hypotheses H5 and H6. Furthermore, the analysis indicated that the adoption of traceability technologies contributes positively to the sustainable performance of olive mills, encompassing economic, environmental and social dimensions, which supported hypothesis H8. However, no significant association was observed between adoption and fraud mitigation, leading to the rejection of H7.

From a practical standpoint, the study also addresses the 'how-to' gap observed in early adoption settings: mill owners may recognize traceability technologies but remain uncertain about which tools should be used for specific security purposes. To mitigate this gap, we provide a technology-to-purpose mapping (Section 3.1.2 and Table 6) that translates the traceability toolbox into actionable control objectives for supply-chain security (serialization, critical tracking events, tamper-evident records, verification at point-of-sale, and risk-based authenticity testing).

From a theoretical perspective, the study contributes by updating and systematizing the debate on traceability technologies in the agri-food sector and by empirically testing a framework that integrates internal and external determinants of technological adoption. By demonstrating that internal organizational factors outweigh institutional pressures in the context of southern Brazil, the research enriches the literature on digital transformation in emerging agricultural industries. From a practical point of view, the study delivers a diagnostic overview of the technological maturity of Brazilian olive mills, highlighting concrete barriers that managers and policymakers must address. The results suggest that investments in training, knowledge dissemination, and consumer education, associated with marketing strategies, may be more effective in encouraging adoption than regulatory incentives alone. In addition, the identification of blockchain and physicochemical methods as technologies with high potential for adoption offers concrete guidance for future investment and innovation strategies.

Methodologically, the research proposed and validated a framework capable of capturing the relationships between different categories of factors and their impacts on sustainability and fraud prevention, offering a replicable model for other contexts. At the same time, it disseminated the findings in a didactic and accessible format to producers and the academic community, reinforcing its educational and extensionist dimension.

Naturally, the study faced some limitations. The sample was restricted to nine mills, selected by purposive non-probabilistic criteria, which, although ensuring diversity of size and location, limits the generalizability of the results. Resource and time constraints also imposed the use of online questionnaires alongside in-person approaches, reducing

opportunities for in-depth engagement with all producers. Future research should therefore expand the sample and apply the methodology to other links in the olive oil value chain, as well as to other geographic regions and agri-food chains, allowing comparative analyses and cross-sectoral validation of the framework. Moreover, given that managers did not perceive a direct association between traceability and fraud mitigation, future investigations should explore in greater detail the mechanisms through which fraud prevention could be enhanced, combining technological solutions with institutional arrangements and educational initiatives.

In summary, this research shows that traceability technologies, while still incipient in southern Brazil, hold strategic potential for the sustainable development of the olive oil industry. Their consolidation will depend not only on overcoming financial barriers, but also on strengthening internal organizational commitment, training, and strategic communication with consumers. By aligning academic reflection with the practical needs of producers, the study advances theoretical knowledge, informs managerial practice, and opens new avenues for research and policy in the digital transformation of agri-food chains. Given the exploratory design and the small, purposive sample (n = 9), the findings should be interpreted as indicative; future studies should incorporate objective fraud-related indicators (e.g., audit/testing records, non-compliance reports, or authentication results) and multi-actor data across the value chain to better capture anti-counterfeiting effects.

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