



Journal home page: <http://ajarcde-safe-network.org> ISSN 2581-0405

# Multi-Level Raw Material Traceability for Cinnamon Supply Chains under Aggregation and Transformation: A Conceptual Model

Fauzan Aulia<sup>1</sup>, Santosa<sup>2\*</sup> and Azrifirwan<sup>2</sup>.

<sup>1</sup> Master Student of Agroindustrial Technology, Faculty of Agricultural Technology, Andalas University, Padang, Indonesia

<sup>2</sup> Department of Agroindustrial Technology, Faculty of Agricultural Technology, Andalas University, Padang, Indonesia

## ARTICLE INFO

### Article History:

Received: 19 December 2025

Final Revision: 07 January 2026

Accepted: 09 January 2026

Online Publication: 17 January 2026

## KEYWORDS

raw material traceability, multi-level traceability, supply aggregation, agro-industrial supply chain

## CORRESPONDING AUTHOR

\*E-mail: [santosa@ae.unand.ac.id](mailto:santosa@ae.unand.ac.id)

## ABSTRACT

The cinnamon agro-industrial supply chain involves multi-source raw material aggregation and transactions among multiple distribution actors, which can compromise provenance continuity, particularly when batch mixing and product transformation occur. This study proposes a conceptual multi-level raw material traceability model for the cinnamon supply chain that explicitly represents hierarchical provenance relationships under such conditions. The study adopts a conceptual modeling approach to represent final-to-source product relationships, source-wise quantitative contributions, and transaction histories across scenarios involving supply aggregation, inter-collector transactions, and industrial transformation. The proposed model structures provenance information hierarchically, enabling traceback of raw materials across multiple supply chain levels despite aggregation processes, ownership transfers, and changes in product form. Conceptual verification indicates that the model preserves provenance continuity and quantitative consistency under complex distribution conditions. The resulting hierarchical traceability structure supports enhanced supply chain transparency and internal quality auditability by enabling reconstruction of raw material composition and origin at each aggregation and transformation stage. This study contributes a conceptual multi-level traceability model that explicitly captures multi-source composition and hierarchical provenance, consistent with the operational characteristics of Indonesia's spice agro-industry, particularly the cinnamon sector.

### Contribution to Sustainable Development Goals (SDGs):

**SDG 8:** Decent Work and Economic Growth

**SDG 9:** Industry, Innovation and Infrastructure

**SDG 12:** Responsible Consumption and Production

**SDG 16:** Peace, Justice and Strong Institutions

## 1. INTRODUCTION

### 1.1. Research Background

The cinnamon agro-industry represents a strategic sector in the development of Indonesia's spice commodities due to its high economic value and steadily increasing global market demand [1]. Indonesia is internationally recognised as a major producer of *Cinnamomum burmannii*, with primary production centres in Sumatra and Jambi [2]. Cinnamon is widely used in the

food, beverage, cosmetic, and pharmaceutical industries; therefore, supply sustainability and the consistency of raw material quality are essential to maintaining the competitiveness of the national agro-industrial sector.

The cinnamon supply chain involves multiple interconnected actors, including farmers as primary producers, collectors as supply aggregators, processing industries, retailers, and end consumers. This structure is inherently complex and non-linear, as raw materials may pass through several aggregation and redistribution stages before reaching industrial processors. In



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practice, collectors frequently aggregate cinnamon bark sourced from numerous farmers with heterogeneous quality characteristics and subsequently redistribute these materials either to other collectors or directly to processing industries. Such practices increase the likelihood of batch mixing, often without comprehensive documentation of raw material origins.

Limited documentation of raw material provenance remains a persistent challenge in the cinnamon agro-industrial supply chain [3]. In many operational settings, traceability records are maintained manually or in a fragmented manner, making it difficult to accurately identify raw material sources, quantify contributions from individual suppliers, and reconstruct transaction histories across supply chain actors [4]. These limitations constrain the ability of agro-industrial stakeholders to verify raw material origins, diagnose causes of quality variation, and support internal quality audits, particularly when non-conformities occur or when detailed provenance information is required by trading partners.

As market expectations increasingly emphasize transparency, accountability, and quality assurance, the need for robust traceability mechanisms within agro-industrial supply chains has become more pronounced. This need is particularly critical for spice commodities such as cinnamon, where variations in geographical origin, cultivation practices, and post-harvest handling significantly influence raw material quality and market value.

## 1.2. Literature Review

Traceability has been widely examined in agro-industrial supply chain management as a mechanism for tracking product movement and associated information. In general, traceability systems are designed to enable upstream identification of raw material origins and downstream tracking of product distribution, thereby supporting quality control, regulatory compliance, and consumer trust [5].

However, many traceability approaches applied in agro-industrial contexts remain relatively simple and are primarily designed for single-level traceability. These systems typically record transactions or product movements at individual stages without explicitly modeling hierarchical relationships between final products and their constituent raw materials [6]. While such approaches may be adequate for linear supply chains with minimal aggregation, they become insufficient in contexts characterized by multi-source aggregation and repeated ownership transfers [7].

In agro-industrial supply chains involving aggregation, raw materials from multiple suppliers are frequently combined into composite batches. When these aggregated materials are redistributed or transformed into derived products, provenance information is often fragmented or lost. Previous studies have shown that conventional batch-based or single-level traceability systems struggle to preserve detailed source attribution under such conditions, particularly when quantitative contributions from individual sources are not explicitly represented [8].

Although various traceability models have been proposed to enhance transparency in food and agricultural supply chains, many emphasize transaction recording rather than structural representation of provenance relationships across multiple supply levels. Consequently, traceability information may indicate product movement without adequately capturing compositional links to upstream raw materials [9]. This limitation restricts the

capacity of agro-industrial actors to conduct comprehensive quality audits, investigate contamination or quality deviations, and demonstrate provenance continuity when raw materials are mixed and transformed [10].

The cinnamon agro-industry exemplifies these challenges due to its reliance on multi-source aggregation, inter-collector transactions, and industrial processing that transforms raw materials into derived products. Despite these characteristics, conceptual traceability models that explicitly address hierarchical provenance and source-wise quantitative contributions under such conditions remain limited in the literature [11].

## 1.3. Research Objective

In response to the limitations identified in existing traceability approaches, this study proposes a conceptual multi-level raw-material traceability model for the cinnamon agro-industrial supply chain. The proposed model is intended to preserve provenance continuity under key operational scenarios, including multi-source aggregation, inter-collector transactions, and transformation of raw materials into derived products.

Specifically, this study seeks to:

- a. Represent hierarchical relationships between final products and their source raw materials across multiple supply chain levels
- b. Document source-wise quantitative contributions of raw materials within aggregated and transformed products, and
- c. Maintain traceability continuity despite batch mixing and repeated ownership transfers among supply chain actors.

The primary contribution of this research is the development of a multi-level traceability model that explicitly captures final product-source relationships and quantitative composition information. In contrast to commonly used single-level traceability approaches, the proposed model provides a structured representation of hierarchical provenance that supports transparency and internal auditability in complex agro-industrial supply chains, particularly in the cinnamon industry.

## 2. MATERIALS AND METHODS

This study adopts a solution-oriented conceptual modelling approach, focusing on developing a raw material traceability structure to address practical challenges in agro-industrial supply chains. The methodology is designed to represent hierarchical raw-material provenance relationships under conditions of supply aggregation, transactions among actors, and the transformation of raw materials into derived products.

### 2.1. Research Approach

The research approach centres on the design and analysis of a conceptual model for raw-material traceability. The primary objective is to formulate traceability structures and mechanisms capable of consistently documenting raw material provenance and enabling traceback across various supply chain scenarios in the cinnamon agro-industry.

Model validation in this study emphasizes logical consistency and preservation of provenance relationships rather than quantitative software performance evaluation. This focus aligns with the research objective, which prioritizes conceptual model development. Model acceptability is assessed based on its ability

to represent provenance relationships comprehensively and coherently across different operational conditions.

The traceability model is developed based on an understanding of business processes in the cinnamon agro-industry involving farmers, collectors, processing industries, and other distribution actors. This grounding in real-world practices supports model relevance, particularly in addressing batch mixing and variability in raw material quality.

## 2.2. Identification of Supply Chain Scenarios

The initial methodological stage involves identifying supply chain scenarios commonly observed in the cinnamon agro-industry. These scenarios provide the foundation for the design of the traceability model to ensure alignment with realistic distribution conditions.

The key scenarios considered in this study include:

- Multi-source raw material aggregation, referring to consolidation of supplies from multiple farmers or collectors with heterogeneous quality characteristics;
- Transactions among peer actors, such as transactions between collectors or among distribution actors prior to delivery to processing industries; and
- Raw material transformation, referring to industrial processing that converts raw materials into derived products, potentially altering product form, units, and characteristics.

Identifying these scenarios ensures that the proposed traceability model can accommodate the complexity of material flows characteristic of the cinnamon agro-industrial supply chain.

## 2.3. Design of the Multi-Level Raw Material Traceability Model

The traceability model is designed by defining key elements that constitute raw material provenance relationships within the supply chain. These elements include products, raw material sources, provenance relationships, quantitative contributions, and transaction histories.

Relationships among these elements are structured hierarchically to enable stepwise traceback of raw material provenance from final products to upstream levels. Under this approach, traceability is not limited to a single relationship level but can be extended across multiple levels as required for analysis, particularly in contexts involving aggregation and raw material transformation.

## 2.4. Model Validation through Prototype-Based Exploration

Model validation is conducted through conceptual exploration using prototype scenarios as analytical tools to examine the logical consistency of traceability relationships. Validation is performed qualitatively by evaluating the model's ability to record and present raw material provenance information across the identified supply chain scenarios.

Prototype-based validation emphasizes preservation of provenance relationships and raw material composition rather than software performance. The model is assessed based on its ability to maintain connectivity between final products and source raw materials, provide structured information on raw material composition, and support traceback of raw material histories for transparency and internal quality auditability. The results of this validation form the basis for subsequent discussion regarding the

relevance and potential applicability of the proposed traceability model in cinnamon agro-industrial management.

## 3. RESULT AND DISCUSSION

### 3.1. Multi-Level Raw Material Traceability Model

The proposed multi-level raw material traceability model is developed to address discontinuities in provenance information that commonly occur in the cinnamon agro-industrial supply chain due to supply aggregation, ownership transfers, and product transformation. The model is grounded in the need to represent raw material relationships hierarchically, enabling the provenance of final products to be consistently traced to upstream sources despite complex and non-linear distribution structures.

### 3.2. Basic Structure of the Traceability Model

The model conceptualizes raw materials and products as interconnected entities linked through explicit provenance relationships. Each product or batch entity is assigned a unique identity, ownership status, and provenance links to one or more source entities. These links represent aggregation, transfer, or transformation processes occurring along the supply chain.

Unlike conventional single-level traceability systems, which typically retain only the most recent supplier information or record transactions in isolation, the proposed model emphasizes hierarchical provenance and multi-source composition. Provenance relationships not only indicate a product's origin but also explicitly record the quantitative contribution of each source. Consequently, raw material composition can be reconstructed at each aggregation level and after transformation, allowing traceback beyond the last supplier even under batch mixing and repeated ownership transfers [12].

At the minimum specification level, the model represents the following core traceability elements:

- Product/Batch batch identity, entity type (raw material/aggregated/derived/final), unit or quantity, and current owner.
- Provenance relationships in the form of parent and child batch links, relationship type (aggregation, transfer, or transformation), quantitative contribution, and temporal or sequence indicators.
- Transactions includes of seller and buyer information, transferred quantity, and transaction time, attached to entities without removing pre-existing provenance relationships.

Figure 1 illustrates a hierarchical traceability structure linking final products to aggregated batches and upstream raw material sources down to the farmer level.

The structure depicted in Figure 1 indicates that each batch entity retains explicit links to its source entities. As a result, raw material composition remains traceable despite aggregation, inter-collector transactions, and industrial transformation. Labels such as *partial transfer* and *input-output/yield* clarify that material transfers and changes in product form can be documented without duplication or loss of provenance context.

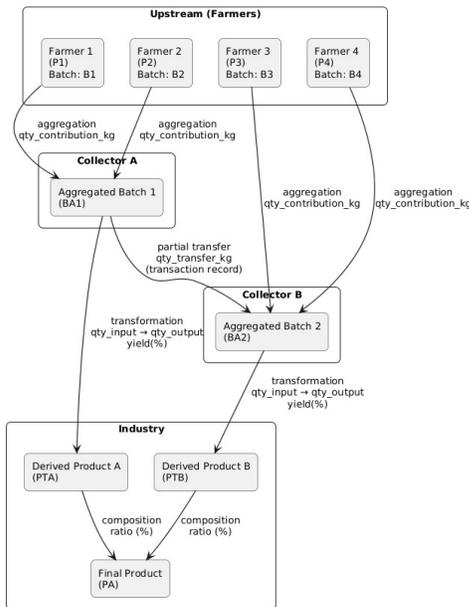


Fig. 1. Illustration of the multi-level traceability model

### 3.3. Model Specification and Quantitative Traceback Computation

This subsection formalizes the proposed model by defining its entities, relationships, and governing constraints to ensure unambiguous provenance reconstruction under aggregation, partial transfer, and transformation scenarios.

The core entities of the model include Product, Batch, Transaction, ProvenanceLink, and Transformation. Each batch represents a traceable aggregation unit, while provenance links explicitly record quantitative contributions between parent and child batches, enabling hierarchical traceback. The model enforces several key constraints, quantitative conservation, prohibition of implicit provenance, integrity under partial transfer, prevention of double counting, and a directed acyclic provenance structure to guarantee consistency and auditability across multiple supply chain levels.

Figure 2 presents the class diagram of the proposed traceability model, illustrating how batch entities are linked through provenance relationships while transaction records are maintained as auxiliary histories that do not alter the underlying provenance structure.

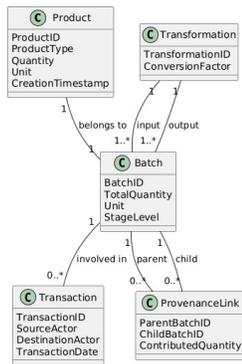


Fig. 2. Class diagram of the proposed multi-level traceability model

To clarify the quantitative specification of provenance links, Table 1 provides an illustrative example based on a BA1–BA2 aggregation and partial transfer scenario. The table shows how raw materials from multiple farmer-level sources are aggregated into batch BA1, partially transferred, and subsequently re-aggregated into batch BA2. Each provenance relationship explicitly records contributed quantities, thereby preventing implicit provenance assumptions and double counting.

Table 1. Example records for BA1–BA2 scenario

Batch					
BatchID	StageLevel	TotalQuantity (kg)	Notes		
B_P1	Farmer	30	Farmer P1 supply		
B_P2	Farmer	20	Farmer P2 supply		
BA1	Collector	50	Aggregated at Collector A (B_P1 + B_P2)		
BA1_T	Collector	25	Transferred portion of BA1 to Collector B		
BA1_R	Collector	25	Remaining portion after split of BA1		
B_P3	Farmer	10	Farmer P3 supply		
B_P4	Farmer	15	Farmer P4 supply		
BA2	Collector	50	Aggregated at Collector B (BA1_T + B_P3 + B_P4)		
ProvenanceLink					
Parent-BatchID	ChildBatchID	ContributedQ quantity (kg)	Interpretation		
B_P1	BA1	30	P1 contributes 30 kg to BA1		
B_P2	BA1	20	P2 contributes 20 kg to BA1		
BA1	BA1_T	25	Portioning BA1 for partial transfer (quantity split)		
BA1	BA1_R	25	Another portion of BA1 after split		
BA1_T	BA2	25	Transferred portion contributes to BA2		
B_P3	BA2	10	P3 contributes 10 kg to BA2		
B_P4	BA2	15	P4 contributes 15 kg to BA2		
Transaction					
TransactionID	SourceActor	DestinationActor	Date	BatchID	Quantity (kg)
T001	Collector A	Collector B	May -1	BA1_T	25

The resulting hierarchical traceback outcome derived from this specification is summarized in Table 2, which reports the source-wise quantitative contributions of farmer-level inputs to batch BA2. The traceback paths shown in the table illustrate how contributions propagate proportionally through intermediate batches based on recorded provenance links.

**Table 2.** Traceback report for BA2

Source (Farmer-level)	Contribution (kg)	Contribution (%)	Traceback path (hierarchical)
P1	15	30%	P1 → BA1 (30/50) → BA1_T (25 kg) → BA2
P2	10	20%	P2 → BA1 (20/50) → BA1_T (25 kg) → BA2
P3	10	20%	P3 → BA2
P4	15	30%	P4 → BA2
Total	50	100%	

The model enforces key constraints, including quantitative conservation, no implicit provenance, partial transfer integrity, no double counting, and a directed acyclic provenance structure. These constraints ensure that provenance relationships remain consistent, auditable, and computationally traceable across multiple aggregation levels.

The traceback computation recursively propagates quantitative contributions through provenance links. Direct inputs contribute their recorded quantities, while indirect inputs propagate in proportion to upstream batch composition.

**3.4. Operational Traceability across Aggregation, Transaction, and Transformation**

At the collector level, cinnamon raw materials are typically sourced from multiple farmers with diverse quality characteristics. The multi-level traceability model enables aggregation from multiple sources to be recorded without eliminating provenance information. Each aggregation is treated as the creation of a new batch entity that retains references to all source products together with their quantitative contributions.

This approach ensures that batch mixing does not break traceability. Instead, it creates new relationships within a hierarchical provenance structure. Consequently, traceback from aggregated batches to individual suppliers remains possible, including reconstruction of the quantitative composition contributed by each source.

The model also accommodates transactions among supply chain actors with equivalent roles, such as transactions between collectors. In this scenario, product transfers are recorded as transaction histories associated with the relevant entities without altering the previously established provenance structure.

Accordingly, the model functions not only as a linear tracking mechanism but also as a representation of distribution networks. Information on transaction counterparts and transferred quantities remains traceable, while links between raw materials and their original sources remain intact. This is particularly relevant because cinnamon supplies often pass through multiple transfer stages before reaching processing industries.

At the industrial level, cinnamon raw materials often undergo transformation into derived products with different forms and characteristics. The model represents transformation as the creation of new product entities that remain linked to source raw materials. Transformation relationships store input-output information (e.g., input quantities, output quantities, and yield values).

This representation preserves traceability of derived products to upstream sources and supports analysis when unit changes, material losses, or yield variation occur. Consequently, traceability does not terminate at production but continues until products are ready for market distribution.

**3.5. Formal Model Definition and Traceback Algorithm**

This section presents the formal definition of the proposed provenance model and the associated traceback algorithm. The formulation is intentionally generic to support applicability across different production structures while preserving quantitative consistency and auditability.

**a. Model Entities and Notation**

Let the production system be represented as a directed acyclic graph composed of batches and provenance links.

- Let  $B = \{b_1, b_2, \dots, b_n\}$  denote the set of all batches.
- Let  $Q(b)$  represent the total quantity associated with batch  $b$ .
- Let  $P = \{p_1, p_2, \dots, p_m\}$  denote the set of original source components.
- Let  $C(b,p)$  denote the quantitative contribution of source component  $p$  within batch  $b$ .

Provenance relationships between batches are represented as directed links

$$L = (b_i \rightarrow b_j, \alpha, y)$$

where:

- $b_i$  is the source batch and  $b_j$  is the derived batch,
- $\alpha \in (0,1]$  denotes the split ratio when a batch is partitioned,
- $y \in (0,1]$  denotes the yield factor when a transformation process occurs.

A provenance link may include either a split ratio, a yield factor, or both, depending on the process semantics.

**b. Quantitative Conservation and Propagation Rules**

The model enforces quantitative conservation and prevents double counting through the following constraints.

**c. Conservation Constraint**

For any batch  $b$ , the sum of all source contributions equals the batch quantity:

$$\sum_{p \in P} C(b, p) = Q(b)$$

**d. Split Rule**

If batch  $b$  is split into a derived batch  $b'$  with ratio  $\alpha$ , the contribution of each source component propagates proportionally:

$$C(b', p) = \alpha \cdot C(b, p)$$

**e. Transformation Rule with Yield**

If batch  $b$  is transformed into batch  $b'$  with yield  $y$ , the propagated contribution is scaled accordingly:

$$C(b', p) = y \cdot C(b, p)$$

These rules ensure that source contributions are preserved proportionally across batch splitting and transformation operations, while explicitly accounting for quantitative loss through yield factors.

**f. Recursive Traceback Algorithm**

Based on the formal model, a recursive traceback algorithm is defined to compute the origin composition of any final batch.

- g. Algorithm: Traceback ( $b_f$ )
1. Initialize an empty contribution map for batch  $b_f$ .
  2. For each incoming provenance link ( $b_i \rightarrow b_f$ ):  
retrieve the contribution map of  $b_i$ ; apply the corresponding split ratio  $\alpha$  and/or yield factor  $y$ ; and dropagate adjusted contributions to  $b_f$ .
  3. Recursively repeat the process for all predecessor batches until raw source batches are reached.
  4. Aggregate contributions by source component.
  5. Return the final contribution map for  $b_f$ .

The algorithm operates with time complexity linear in the number of provenance links and is independent of the depth of the production network. This enables efficient traceback even in deeply nested multi-stage processing systems.

Conceptually, the proposed model enhances supply-chain transparency by providing complete and structured records of raw material movement and reconstructable composition information. The model also supports internal quality auditability by enabling industries to trace source contributions when quality variation or non-conformities occur. Such information is valuable for quality control, supplier evaluation, and improving long-term supply reliability.

### 3.6. Traceability under Aggregation and Inter-Collector Transaction Scenarios

This section demonstrates the application of the proposed multi-level traceability model under aggregation and inter-collector transaction scenarios. These scenarios reflect operational conditions in which raw materials circulate among multiple distribution actors before reaching processing industries and present a high risk of provenance discontinuity due to batch mixing and ownership transfers.

#### 3.7. Supply Chain Scenario Description

In the illustrated scenario, several farmers supply cinnamon raw materials to Collector A in varying quantities and with heterogeneous quality characteristics. Collector A aggregates these supplies into a single batch to meet volume requirements. Subsequently, a portion of the aggregated batch is sold to Collector B through an inter-collector transaction. Collector B may retain the materials as inventory or perform further aggregation before delivering them to processing industries.

This scenario highlights that raw materials do not necessarily flow directly from farmers to processing industries. Under such conditions, traceability systems that record only the most recent supplier are likely to lose critical upstream provenance information, particularly when partial transfers and re-aggregation occur.

#### 3.8. Model Application to Multi-Source Aggregation

Aggregation conducted by Collector A is modeled as the formation of a new batch entity that maintains explicit provenance relationships with all contributing source products. Each farmer's supply is recorded as a distinct source component with a defined quantitative contribution to the aggregated batch.

Through this representation, aggregation does not eliminate provenance information but consolidates it within a structured traceability framework. When traceback is required, actors can retrieve detailed batch composition data, including the quantitative contributions of individual farmers. This ensures that aggregation processes remain fully traceable and auditable.

### 3.9. Traceability in Inter-Collector Transactions

When Collector A transfers part of an aggregated batch to Collector B, the transaction is recorded as a transfer history associated with the relevant batch entity. Importantly, the ownership transfer does not modify or overwrite existing provenance relationships.

As a result, Collector B receives raw materials together with their embedded provenance context rather than as decontextualized physical goods. This mechanism enables continuity of traceability across actors with equivalent roles and ensures that inter-collector transactions enrich the provenance record without breaking links to original sources. Such functionality is particularly relevant in cinnamon supply chains, where materials frequently undergo multiple redistribution stages prior to industrial processing.

#### 3.10. Prototype-Based Model Verification

As a form of conceptual verification, the proposed model is applied to a prototype scenario to evaluate whether provenance relationships and quantitative composition are preserved across aggregation, inter-collector transfers, and industrial transformation. The walkthrough follows the process illustrated in Figure 1 and is structured according to operational phases.

- a. Upstream supply and initial aggregation (Collector A)  
Farmer P1 supplies 30 kg of raw material and Farmer P2 supplies 20 kg to Collector A. Collector A aggregates these inputs into batch BA1 with a total quantity of 50 kg. The recorded composition of BA1 is P1: 30 kg (60%) and P2: 20 kg (40%). BA1 constitutes a single batch entity with explicit source-wise quantitative provenance.
- b. Partial batch transfer and secondary aggregation (Collector B)  
A partial quantity of BA1 (25 kg) is transferred from Collector A to Collector B. The model records this event as a transaction while preserving BA1's internal composition (P1 60%, P2 40%) for the transferred portion.  
Collector B also receives additional raw materials consisting of 10 kg from Farmer P3 and 15 kg from Farmer P4. These inputs are aggregated together with the transferred portion to form batch BA2 with a total quantity of 50 kg. The resulting hierarchical provenance composition of BA2 is P1 (15 kg), P2 (10 kg), P3 (10 kg), and P4 (15 kg). Transferred batches can be combined with new supplies without loss of upstream provenance information.
- c. Industrial transformation  
The remaining portion of BA1 retained by Collector A (25 kg) is processed into product PTA, while batch BA2 (50 kg) is processed into product PTB. Transformation records explicitly document input-output relationships, for example, BA2 input of 50 kg resulting in PTB output of 45 kg.

Yield values are recorded as part of the transformation process, while provenance links to upstream sources are

- preserved. This allows raw material origin to be reconstructed after processing despite changes in quantity.
- d. Traceback from the final product

The final product batch PA has a total quantity of 70 kg and is composed of two upstream products: PTA (25 kg) and PTB (45 kg). The traceback procedure propagates quantitative contributions from these batches to their respective source components.

For PTA, which originates from BA1 through a split operation with a ratio of 0.5, batch BA1 contains two source components: P1 (60%) and P2 (40%). Applying the split rule yields the following contributions:

$$P1: 0.6 \times 25 = 15 \text{ kg}$$

$$P2: 0.4 \times 25 = 10 \text{ kg}$$

For PTB, which is produced by transforming BA2 with a yield factor of 0.9, the propagated contributions are:

$$P1: 15 \times 0.9 = 13.5 \text{ kg}$$

$$P2: 10 \times 0.9 = 9 \text{ kg}$$

$$P3: 10 \times 0.9 = 9 \text{ kg}$$

$$P4: 15 \times 0.9 = 13.5 \text{ kg}$$

Aggregating contributions from PTA and PTB, the final product PA contains:

$$P1: 28.5 \text{ kg}$$

$$P2: 19 \text{ kg}$$

$$P3: 9 \text{ kg}$$

$$P4: 13.5 \text{ kg}$$

The total equals 70 kg, confirming quantitative conservation and demonstrating that the model avoids double counting while maintaining complete provenance traceability

### 3.11. Benefits under Complex Distribution Conditions

Application of the proposed model under aggregation and inter-collector transaction scenarios demonstrates its ability to preserve provenance continuity despite batch mixing and ownership transfers. Distribution transparency is enhanced, as downstream actors can verify raw material origins and quantitative contributions with greater accuracy [13].

Furthermore, traceability at the collector level supports internal audits and supplier evaluation by providing structured and reconstructable provenance information. This enables more informed quality control, improved supplier management, and more robust decision-making under complex distribution conditions [14].

### 3.12. Implications for Transparency and Quality Auditability

The proposed multi-level traceability model provides important implications for enhancing transparency and quality auditability in the cinnamon agro-industrial supply chain. By structuring provenance information hierarchically, the model improves visibility of raw material flows and composition across distribution and processing stages. This structured representation enables actors to access consistent and reconstructable provenance information even under conditions of aggregation, redistribution, and transformation.

### 3.13. Enhancement of Supply Chain Transparency

Supply chain transparency is strengthened through the model's ability to represent complete raw material journey records from upstream to downstream stages. Aggregation, inter-collector transactions, and transformation processes are captured within interconnected traceability structures rather than isolated transaction logs. As a result, transparency is reflected in the availability of end-to-end provenance records that allow downstream actors to trace products not only to their immediate suppliers but also to farmer-level sources.

Such transparency reduces information asymmetry among supply chain actors. Processing industries and retailers gain clearer insights into the origins and composition of the raw materials they receive, supporting more accountable procurement coordination and improved supply chain governance [15].

### 3.14. Support for Raw Material Quality Auditability

Quality auditability is a key benefit of the proposed model, as provenance information is documented in a structured, quantitative, and traceable manner. When quality variation or non-conformities occur, agro-industrial actors can perform traceback to identify contributing sources and determine their quantitative contributions to specific batches or products [16].

In this context, auditability is characterized by the model's ability to reconstruct both *source composition* (which suppliers contributed) and *quantitative composition* (how much each supplier contributed). This capability provides a reliable basis for supplier evaluation, investigation of quality deviation causes, and systematic improvement of procurement practices. Consequently, quality audits can be applied not only reactively but also as part of continuous quality management.

### 3.15. Implications for Agro-Industrial Decision Making

Availability of comprehensive traceability information supports more informed decision making in agro-industrial management. Industries can utilize provenance and contribution data to develop more selective procurement strategies, prioritize suppliers with consistent quality performance, and manage supply risks more effectively.

Information on source-wise contributions enables identification of suppliers with the greatest influence on product quality, thereby supporting targeted quality interventions. In addition, the traceability structure facilitates evaluation of distribution strategies and aggregation practices, contributing to more resilient and transparent supply chain operations.

### 3.16. Limitations and Future Research Directions

Despite its conceptual advantages, the proposed model has limitations. The evaluation conducted in this study remains qualitative and focuses on logical consistency and preservation of provenance relationships rather than empirical implementation outcomes. Economic impacts, adoption barriers among supply chain actors, and integration with formal certification or regulatory standards are not examined in depth.

Future research should extend the model to larger-scale operational environments, assess its practical implementation using real transaction data, and evaluate its contributions to supply chain efficiency, quality assurance, and competitiveness.

Further studies may also explore integration of the proposed traceability structure with formal quality management systems and digital traceability platforms.

#### 4. CONCLUSION

This study proposes a multi-level raw material traceability model that represents hierarchical provenance in the cinnamon agro-industrial supply chain. The model explicitly captures multi-source aggregation, inter-collector transactions, and raw material transformation while preserving provenance continuity. The results demonstrate that, compared to conventional single-level traceability approaches, the proposed model enables more comprehensive reconstruction of raw material composition through explicit source-wise quantitative relationships. Hierarchical traceback allows provenance analysis to extend upstream to farmer-level sources, supporting raw material quality auditability, supplier evaluation, and informed decision making under complex distribution conditions. The main contribution of this study lies in the conceptual design of a hierarchical, multi-source traceability structure that enhances transparency and auditability in aggregated agro-industrial supply chains. However, the study remains qualitative in nature. Future research should focus on empirical implementation and evaluation of the model's impact on supply chain efficiency, quality management, and integration with formal traceability or certification systems.

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