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Title

**Indexation des mégadonnées basée IoT dans la chaîne d'approvisionnement
alimentaire / Indexing Big Data Based on IoT in Food Supply Chain**

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ABSTRACT

During the industrial revolution, ensuring food safety has become a critical concern, where the primary objective is to improve the quality of life and safety of citizens. This objective is challenged by the complexity of supply chain processes, which involve the collection of big data from multiple stages and actors, as well as inefficiencies in monitoring and traceability mechanisms that rely on technologies such as IoT and ICT. Alongside these technological factors, Blockchain technology has emerged as a promising solution, offering secure, tamper-proof, and transparent data management across supply chain stages. However, scalability issues hinder traceability query efficiency, as searches must be performed sequentially across blocks. This Ph.D thesis addresses this limitation by developing indexing techniques for big data in the food supply chain to optimize search processes and enhance traceability performance. The first contribution integrates the B-tree indexing technique with the blockchain by introducing a modified transaction structure that records fabrication time and computes per-block ranges. The B-tree structure manages these fabrication time ranges together with their corresponding block numbers, which are continuously updated with each new block until they cover the entire blockchain network. This approach enables the system to efficiently locate relevant blocks containing traceability data, allowing queries to be executed only within the identified blocks, thereby optimizing inter-block searches. The second contribution presents a novel blockchain-based traceability system that combines Natural Language Processing (NLP) with B+ tree indexing, where NLP interprets consumer text queries to identify target supply chain stages and the B+ tree index narrows searches to relevant blocks, ensuring accurate and efficient responses. The third contribution proposes the MerkleB+ tree (MB+ tree), a hybrid structure designed to optimize big data transaction management within each block, reducing linear scans while preserving the security guarantees of the Merkle tree. The simulation of these three systems was conducted using the Hyperledger Fabric framework, which supports food supply chain scenarios and enables the creation of a decentralized network based on our specifications. Performance testing under various network configurations showed that the three systems demonstrated significant improvements in query efficiency, providing faster and more reliable access to traceability information, as well as superior performance compared to existing methods.

Key-words: Food Supply Chain, Indexing techniques, Blockchain, B-tree, B+ tree, Natural Language Processing, MerkleB+ tree, Hyperledger Fabric.

RÉSUMÉ

Depuis la révolution industrielle, garantir la sécurité alimentaire est devenue une préoccupation majeure visant à améliorer la qualité de vie et la sécurité des citoyens. Cet objectif est freiné par la complexité des processus de la chaîne d’approvisionnement, la génération massive de données à différentes étapes et les limites des mécanismes de suivi et de traçabilité basés sur l’IoT et les TIC. La technologie blockchain s’est imposée comme une solution prometteuse, offrant une gestion des données sécurisée, transparente et inviolable. Toutefois, son intégration pose des problèmes d’évolutivité qui réduisent l’efficacité des requêtes de traçabilité, car les recherches doivent être effectuées séquentiellement sur plusieurs blocs. Cette thèse de doctorat aborde cette limitation en développant des techniques d’indexation pour le big data dans la chaîne d’approvisionnement alimentaire afin d’optimiser les processus de recherche et d’améliorer les performances de traçabilité. La première contribution intègre la technique d’indexation B-tree à la blockchain en introduisant une structure de transaction modifiée qui enregistre le temps de fabrication et calcule les plages par bloc. La structure B-tree gère ces plages de temps de fabrication ainsi que les numéros de bloc correspondants, qui sont continuellement mis à jour à chaque nouveau bloc jusqu’à couvrir l’ensemble du réseau blockchain. Cette approche permet au système de localiser efficacement les blocs pertinents contenant des données de traçabilité, permettant ainsi d’exécuter des requêtes uniquement au sein des blocs identifiés, optimisant ainsi les recherches inter-blocs. La deuxième contribution présente un nouveau système de traçabilité basé sur la blockchain qui combine le traitement automatique du langage naturel et l’indexation B+. Le traitement automatique du langage naturel interprète les requêtes textuelles des consommateurs pour identifier les étapes cibles de la chaîne d’approvisionnement, tandis que l’indexation B+ restreint les recherches aux blocs pertinents, garantissant ainsi des réponses précises et efficaces. La troisième contribution propose l’arbre MerkleB+ (arbre MB+), une structure hybride conçue pour optimiser la gestion des transactions Big Data au sein de chaque bloc, réduisant les analyses linéaires tout en préservant les garanties de sécurité de l’arbre Merkle. Les simulations de ces trois systèmes, réalisées avec le framework Hyperledger Fabric, ont démontré une amélioration significative de l’efficacité et de la fiabilité des requêtes par rapport aux méthodes existantes.

Mots-clés : Chaîne d’approvisionnement alimentaire, Techniques d’indexation, Blockchain, B-tree, B+ tree, Traitement automatique du langage naturel, MerkleB+, Hyperledger Fabric.

ملخص

خلال الثورة الصناعية، أصبح ضمان سلامة الغذاء شاغلاً بالغ الأهمية، حيث يتمثل الهدف الرئيسي في تحسين جودة حياة المواطنين وسلامتهم. يواجه هذا الهدف تحديات بسبب تعقيد عمليات سلسلة التوريد، التي تنطوي على جمع بيانات ضخمة من مراحل وعناصر متعددة، بالإضافة إلى عدم كفاءة آليات الرصد والتتبع التي تعتمد على تقنيات مثل إنترنت الأشياء وتكنولوجيا المعلومات والاتصالات. إلى جانب هذه العوامل التكنولوجية، برزت تقنية البلوك تشين كحل واعد، حيث توفر إدارة بيانات آمنة ومقاومة للتلاعب وشفافة عبر مراحل سلسلة التوريد. ومع ذلك، فإن مشكلات قابلية التوسع تعيق كفاءة استعلامات التتبع، حيث يجب إجراء عمليات البحث بشكل تسلسلي عبر الكتل. تتناول أطروحة الدكتوراه هذه هذا القيد من خلال تطوير تقنيات فهرسة للبيانات الضخمة في سلسلة توريد الأغذية لتحسين عمليات البحث وتعزيز أداء التتبع. تُدمج المساهمة الأولى تقنية فهرسة B-tree مع سلسلة الكتل من خلال تقديم بنية معاملات معدلة تُسجل وقت التصنيع وتحسب نطاقات كل كتلة. تُدير بنية B-tree هذه النطاقات الزمنية للتصنيع مع أرقام الكتل المُقابِلة لها، والتي تُحدَّث باستمرار مع كل كتلة جديدة حتى تُغطي شبكة سلسلة الكتل بأكملها. يُمكن هذا النهج النظام من تحديد مواقع الكتل ذات الصلة التي تحتوي على بيانات التتبع بكفاءة، مما يسمح بتنفيذ الاستعلامات داخل الكتل المُحددة فقط، مما يحسّن عمليات البحث بين الكتل. تُقدّم المساهمة الثانية نظام تتبع مُبتكراً قائماً على سلسلة الكتل يجمع بين معالجة اللغة الطبيعية (NLP) وفهرسة B+ Tree، حيث تُفسّر NLP استعلامات نصوص المستهلكين لتحديد مراحل سلسلة التوريد المُستهدفة، ويُضيق فهرس B+ Tree نطاقات البحث إلى الكتل ذات الصلة، مما يضمن استجابات دقيقة وفعالة. تقترح المساهمة الثالثة شجرة MerkleB+ (MB+) وهي بنية هجينة مُصممة لتحسين إدارة معاملات البيانات الضخمة داخل كل كتلة، مما يُقلل من عمليات المسح الخطية مع الحفاظ على ضمانات أمان شجرة Merkle. أُجريت محاكاة هذه الأنظمة الثلاثة باستخدام إطار عمل Hyperledger Fabric، الذي يدعم سيناريوهات سلسلة توريد الأغذية ويُمكن من إنشاء شبكة لامركزية بناءً على مواصفاتها. أظهر اختبار الأداء باستخدام تكوينات شبكة مختلفة أن الأنظمة الثلاثة أظهرت تحسينات ملحوظة في كفاءة الاستعلام، مما يوفر وصولاً أسرع وأكثر موثوقية لمعلومات التتبع، بالإضافة إلى أداء متفوق مقارنةً بالطرق الحالية.

الكلمات المفتاحية: سلسلة التوريد الغذائية، البيانات الضخمة، تقنيات الفهرسة، سلسلة الكتل، B-tree، B+ Tree، معالجة اللغة الطبيعية، MerkleB+ tree، Hyperledger Fabric.

ABBREVIATIONS

AI	Artificial Intelligence
API	Application Programming Interface
BW	Bag of Words
CLI	Command Line Interface
DDDM	Data-Driven Decision Making
DeFi	Decentralized Finance
DERs	Distributed Energy Resources
DDoS	Distributed Denial of Service
DoS	Denial of Service
DPOS	Delegated Proof of Stake
EMR	Electronic Medical Record
FSC	Food Supply Chain
GPS	Global Positioning System
IBBA	IoT-Blockchain-Big Data-Artificial Intelligence Framework
ICT	Information and Communication Technology
IPFS	InterPlanetary File System
IoT	Internet of Things
MBR	Minimum Bounding Rectangle
MB+	Merkle B+ Tree
MHT	Merkle Hash Tree
MPT	Merkle Patricia Tree
NFC	Near Field Communication
NLP	Natural Language Processing

PBFT	Practical Byzantine Fault Tolerance
P2P	Peer-to-Peer
PoA	Proof of Authority
PoS	Proof of Stake
PoW	Proof of Work
QR	Quick Response (Code)
RECs	Renewable Energy Certificates
RF	Random Forests
RFID	Radio Frequency Identification
SDK	Software Development Kit
SHA256	Secure Hash Algorithm 256-bit
SPV	Simplified Payment Verification
SVM	Support Vector Machines
TF-IDF	Term Frequency–Inverse Document Frequency
WE	Word Embeddings
WSN	Wireless Sensor Network

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INTRODUCTION

The rapid growth of the food sector and advancements in materials and logistics within the food supply chain, as well as risks related to data security and integrity, make food safety for consumers a major challenge [251, 281]. In addition, ensuring traceability and transparency throughout the supply chain process is a critical concern, as it involves knowing all historical data and requires the communication and management of critical information by precisely identifying the origin and various information exchanges [56].

The supply chain process in the food sector is highly complex, involving multiple actors distributed across various stages from farm to table [16, 361]. These stages encompass production, distribution, retail, and consumption. At every step, information about the food products is collected to ensure its traceability and transparency, thereby fostering greater trust between consumers and food organizations [62]. Through traceability queries, consumers can retrieve detailed information about products from each step in the supply chain, enhancing their understanding of the products they consume [63]. This mechanism improves the quality control of food managed by various actors in the chain, facilitates the isolation of contaminated products and aids in fraud detection [151].

Traditional traceability systems in the food supply chain lack decentralization, as they manage and store all data on centralized servers, which are less secure and vulnerable to tampering [413]. Although some systems use Internet of Things (IoT) to extract and track big data in the supply chain, they cannot guarantee transparency and reliability to consumers [15, 54, 455]. Therefore, these traditional models have not addressed consumer concerns about the safety of food products [305].

The blockchain technology has gradually expanded from cryptocurrency fields to the food supply chains, offering a new solution for enhancing decentralization, traceability, and ensuring food safety for consumers [109, 279]. While blockchain has achieved remarkable success, blockchain queries require sequential navigation across blocks to locate specific information and can lead to performance slowdowns as the number of blocks grows [468].

Several studies have proposed to enhance the search efficiency by modifying the data structure within the blockchain or integrating it with external databases like IPFS [325, 451] and cloud servers [337]. Although these approaches have reduced search time, they have also increased blockchain storage requirements and compromised its security features. In addition, these solutions are not efficient in the context of the food supply chain, where the complexity often requires traceability queries to traverse longer chains, resulting in persistent time overheads without optimization. Furthermore, there has been limited research on the use of integrated indexing techniques to streamline blockchain traceability queries and improve food traceability

which serves as this thesis's main topic. In this thesis, we aim to address the limitations of traceability queries and improve the efficiency of query processing within the food supply chain by integrating indexing techniques into traceability systems based on blockchain technology. This integration should be guided by new perspectives on big data management and traceability queries across the stages of the food supply chain. The long-term objective of this perspective is to address the following core issues:

- ❖ Since the food supply chain involves a large number of stages and actors, it becomes difficult to rapidly extract and trace relevant data. Therefore, it is necessary to design and implement an indexing-based approach that optimizes traceability queries within food supply chain systems.
- ❖ Given that blockchain technology generates a large number of secure and immutable blocks represents the food supply chain, it is essential to improve the efficiency of inter-block data retrieval by integrating indexing techniques with blockchain, ensuring both scalability and secure transaction searches.
- ❖ As blockchain-based food supply chains generate vast amounts of data, efficient intra-block query mechanisms are required to optimize traceability searches within individual blocks.

In this Ph.D thesis, we made several contributions toward achieving the desired objectives. The major contributions can be summarized as follows:

- ✍ **First contribution:** The first contribution proposed a new blockchain-based traceability system built on the Hyperledger Fabric framework, aimed at improving the search efficiency for traceability data in the food supply chain process. Our system is designed using an external indexing technique based on a B-tree structure, which efficiently manages the large number of blocks and optimizes inter-block query time by retrieving relevant blocks. The experimental results demonstrate a significant improvement in traceability queries within the blockchain compared to traditional approaches that scan all blocks in the ledger. This enhancement contributes to ensure food safety for consumers in the food supply chain.
- ✍ **Second contribution:** We propose a new blockchain-based traceability system that integrates a Natural Language Processing (NLP) model and an indexing technique. The NLP model processes consumer textual queries to extract the desired information and meet the consumer demand for comprehensive and timely information. In addition, a B+ tree index is created in the last block of the blockchain as a dedicated structure generated from transaction data within the blockchain and is continuously updated with the creation of new blocks until the final version of the index is established. Our system optimizes the search process across a large number of blocks by identifying and returning the addresses of the blocks corresponding to the specific supply chain stage mentioned in the consumer's text query and intra-block queries are then performed only within these identified blocks.
- ✍ **Third contribution:** We have introduced a novel approach about intra-block queries that require a fine-grained mechanism to eliminate sequential scanning of transactions and to efficiently search, filter, and retrieve desired information within the transaction list of a given block. We propose the integration of a B+ tree indexing structure with the Merkle tree within each block. This hybrid design aims to enhance search speed, reduce linear scans, and enable low-latency access to traceability data, while preserving the security guarantees offered by the Merkle tree.

The remainder of this thesis is organized into two main parts, each containing several chapters. The first part presents the state-of-the-art, divided into three chapters, while the second part outlines the proposed contributions, organized into three chapters. Finally, the thesis concludes with a general conclusion.

❖ Part I: Backgrounds, Preliminaries and Basic Concepts

□ *Chapter 01: “Food Supply Chain and Food Safety”*

This chapter introduces the fundamental concepts of the food supply chain and its critical connection to food safety. It begins with an overview of the food supply chain process, including its origin, definition, features, and architecture. The chapter then examines the concept of food safety, highlighting its definition, common risks and hazards, and the challenges faced in maintaining safety throughout the supply chain then various mechanisms for ensuring food safety are also discussed. Finally, the chapter identifies key challenges and research gaps that motivate the need for innovative solutions, setting the foundation for the contributions presented in the subsequent chapters.

□ *Chapter 02: “Blockchain Technology: Fundamentals and Integration in Food Supply Chain”*

This chapter explore the fundamentals of blockchain, including its history, definition, features, architecture, and various applications across industries. Then its focus to the food supply chain context, discussing how blockchain can be integrated to enhance transparency, trust and present the architecture of blockchain-based food supply chains, along with their benefits and real-world applications. The chapter concludes by highlighting the challenges and limitations of applying blockchain to large-scale food systems, setting the stage for the need for advanced data management and query optimization techniques.

□ *Chapter 03: “Blockchain Query Management and Indexing Technique”*

Addresses query management in blockchain systems with a focus on indexing techniques that enable efficient information retrieval. The chapter reviews the three major areas when we can optimize the search process in blockchain systems, with further distinguishes between intra-block and inter-block queries, outlining the specific challenges each level poses. Additionally, fundamentals of indexing are then presented, including definitions, objectives, types of indexing structures, and query types relevant to blockchain environments. Finally, evaluation metrics such as search performance, update performance, and storage overhead are examined, providing the foundation for developing optimized indexing mechanisms to support scalable and efficient query processing in blockchain-based food supply chains.

❖ Part II: Contributions

□ *Chapter 04: “B-Tree Indexing Approach in Blockchain-based Food Supply Chain to Improve Traceability Query”*

This chapter introduces a B-tree indexing model designed to enhance traceability queries within blockchain-based food supply chain systems. After presenting related works on blockchain-based traceability and query optimization systems, the proposed architecture is detailed, including the blockchain design, the B-tree index structure,

and its integration with traceability queries. The chapter then presents and discusses the results obtained from the evaluation of the proposed system.

□ *Chapter 05: “B+ Tree Indexing and NLP Model in Blockchain-based Food Supply Chain to Improve Traceability Query”*

This chapter extends the work by combining B+ tree indexing with natural language processing (NLP) to further improve traceability query performance. It presents the architecture and design of each component of this system, followed by the steps of optimized traceability query. Finally, it presents the results of this system and discussed the evaluation of the proposed system.

□ *Chapter 06: “MerkleB+ Tree for Intra-block Query Optimization”*

In this chapter, we proposes a MerkleB+ tree (MB+ tree) structure to specifically optimize intra-block query processing in blockchain-based food supply chains. The design of the MB+ tree and its query process are described in detail, followed by experimental evaluation and discussion.

Part I

Backgrounds, Preliminaries and Basic Concepts

CHAPTER 1

FOOD SUPPLY CHAIN AND FOOD SAFETY

Chapter contents

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1.1 Introduction

In recent decades, the food sector has experienced rapid transformation due to globalization, population growth, and changing consumer expectations. These developments have placed increasing pressure on food supply chains (FSCs) to not only ensure the efficient movement of goods from producers to consumers but also to guarantee the safety, quality, and transparency of food products throughout their journey. This chapter lays the foundation for understanding the structure and functioning of the food supply chain and its digital transformation. It explores the process architecture, key stages, and involved stakeholders, highlighting the complexity of interactions and data flows across different levels. The chapter also examines the concept of food safety, along with its challenges, sources of risks, and potential hazards, as well as the mechanisms used to address these issues all aimed at ensuring a reliable response to food safety concerns.

1.2 Food Supply Chain Process

The food supply chain represents a vital infrastructure in the food industry, consisting of a complex structure of interconnected components that requires comprehensive study. Recent research has increasingly focused on ensuring food safety throughout this chain, examining various innovative solutions and technological approaches to address emerging challenges.

1.2.1 Origin and Evolution

The concept of the food supply chain (FSC) has evolved from simple, localized exchanges when communities relied on seasonal harvests and direct trade between producers and consumers to a complex, global, and technologically advanced system [198, 322, 334]. This transformation reflects significant digital advancements, along with emerging challenges and needs within the food industry sector. To better illustrate this evolution, Table 1.1 presents a comparison of key historical phases, highlighting the changes in food supply chain processes over time.

This historical progression clearly illustrates how the food supply chain has shifted from traditional, community-based systems to globally interconnected networks supported by technological innovations, highlighting the critical need to study this process and its various components.

Period	Key Developments
18th–19th Century	<ul style="list-style-type: none"> • Emergence of formal food distribution during the Industrial Revolution • Mechanization, railways, and preservation techniques enabled longer-distance transport
Early 20th Century	<ul style="list-style-type: none"> • Growth of food processing industries and urban food networks • Establishment of retail channels and early cold chain infrastructure
Mid to Late 20th Century	<ul style="list-style-type: none"> • Expansion of supermarkets with standardized packaging systems • Development of global sourcing focused on affordability and availability
2000s	<ul style="list-style-type: none"> • Intensified globalization and urbanization of supply chains • Emergence of international networks for year-round consumer demand
2003–2007	<ul style="list-style-type: none"> • FAO recognition of FSCs' critical role in food safety and economics • New emphasis on traceability standards and risk management
2020–Present	<ul style="list-style-type: none"> • World Economic Forum's push for digital supply chain transformation • COVID-19 pandemic accelerating digitization and resilience needs
Current Era	<ul style="list-style-type: none"> • Integration of ICT, IoT, and advanced data analytics solutions • Growing focus on safety, sustainability, and consumer trust metrics

TABLE 1.1: Food supply chain history and evolution

1.2.2 Definition

Since the emergence of the food supply chain, several international organizations and research institutions have contributed to the development of a common definition. Over time, various definitions have been proposed based on different criteria such as data, actors, and services reflecting the complexity and evolution of the food sector (see Figure 1.1) [55, 372, 409].

In this section, we present some of the most widely cited definitions of the food supply chain process found in the literature.

- According to Food and Agriculture Organization (2008), the food supply chain process is defined as:

"The sequence of processes and flows that take place to move food from the primary producer to the final consumer, encompassing production, processing, packaging, storage, transportation, distribution, and retail stages."

— FAO [115]

- Beamon et al. (1998) offers a broader supply chain perspective, defining it as:

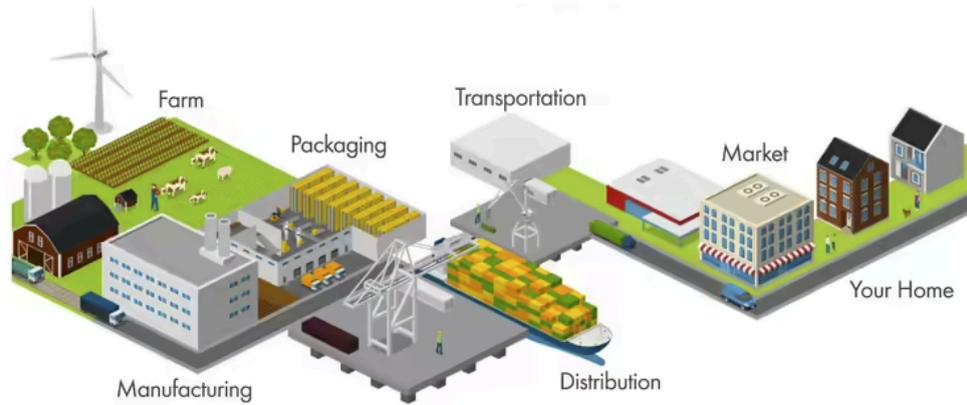


FIGURE 1.1: Food supply chain process

"An integrated process in which a number of different business entities (i.e., suppliers, manufacturers, distributors, and retailers) work together in an effort to: (1) acquire raw materials, (2) convert these raw materials into specified final products, and (3) deliver these final products to retailers."

— Beamon et al. [50]

- When applied to the food industry, this process must take into account the unique characteristics of food products especially perishability and safety. A more recent definition by Trienekens et al. (2012) emphasizes the food supply chain as:

"A network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of food products and services for consumers."

— Trienekens et al. [401]

- Based on the above definitions, we summarize the concept of the food supply chain as follows:

"The food supply chain process in the food sector is distributed process, involving multiple actors distributed across various stages from farm to table. It encompasses a wide range of interconnected activities, starting from agricultural production and continuing through processing, storage, transportation, wholesale, retail, and finally consumption. At every step, information and data about the food products is collected and managed by numerous stakeholders who contribute to various operations across multiple stages thereby plays a critical role in maintaining the quality, safety, and availability of food products"

These definitions agree on the idea that the food supply chain is not just a logistics system, but a value creation and risk management network involving multiple actors and dynamic processes.

1.2.3 Features

The food supply chain is a unique and complex system that differs significantly from other types of supply chain due to several factors, including the sensitive nature of its products, the

diversity of stakeholders involved, and the strict regulatory environment it must comply with. Understanding the fundamental features and operational characteristics of the FSC is essential for identifying its vulnerabilities and exploring opportunities for technological enhancement. Table 1.2 provides a comparative overview of various supply chains based on multiple features, highlighting the importance of studying the food supply chain.

Comparison Factor	Food Supply Chain	Pharmaceutical Supply Chain	Electronics Supply Chain
Product Vulnerabilities	Spoils quickly (days) Needs cold storage Weather-sensitive	Expires (months-years) Temperature-controlled Light-sensitive	Long-lasting Fragile components Heat/moisture risks
Safety Impact	Can make people sick Causes foodborne illness Allergen risks	Incorrect doses dangerous Fake medicines deadly Sterility critical	Malfunctions costly Battery fires possible Data security risks
General Needs	Full traceability Temperature monitoring Quick delivery	Batch tracking Tamper-proof packaging Expiry management	Quality testing Anti-counterfeit marks Version control
Regulations	Food safety agencies Hygiene standards Import inspections	Drug approval systems Pharmacy laws Prescription rules	Recycling laws Hazardous material bans Trade compliance
Risks/Limitations	Adulteration common False labeling issues \$50B/year fraud impact	Counterfeit drugs \$200B illegal market Supply shortages	Fake components Grey market sales Rapid obsolescence

TABLE 1.2: Comparative analysis of supply chain types

Perishability of Food Products

One of the defining characteristics of the food supply chain is the perishability of its products, where the food items typically have complex compositions, limited shelf lives, and are highly sensitive to time and storage conditions. Moreover, the degree of perishability differs significantly among various food categories [89, 156]. Figure 1.2 presents a taxonomy of food categories in the supply chain, classifying them based on their perishability.

Related studies on food perishability classify product types based on their sensitivity to spoilage and storage constraints. These classifications are synthesized and shows that fruits and vegetables are the most frequently cited category in perishability research, accounting for approximately 42% of the total. Dairy products follow with around 26%, while other highly perishable items such as meat, poultry, and seafood collectively represent about 25% of all perishable product categories discussed in the literature (see Figure 1.3) [48, 250].

- **Fruits and Vegetables:** Are among the most perishable items in the food supply chain with rapid deterioration of quality after harvest due to natural respiration, moisture loss, and microbial growth. They require controlled storage conditions in transport or distribution stage such as low temperatures and proper ventilation to minimize spoilage and preserve nutritional value [283].

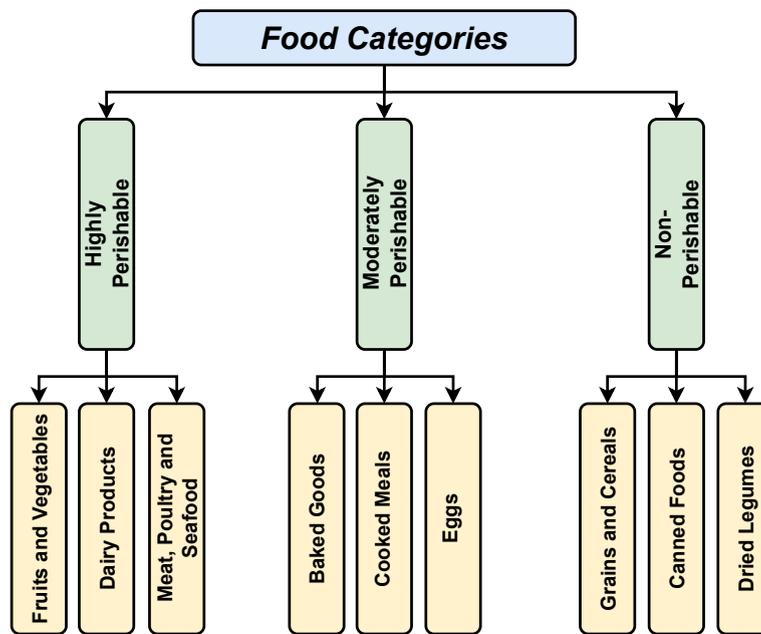


FIGURE 1.2: Classification of food categories by perishability

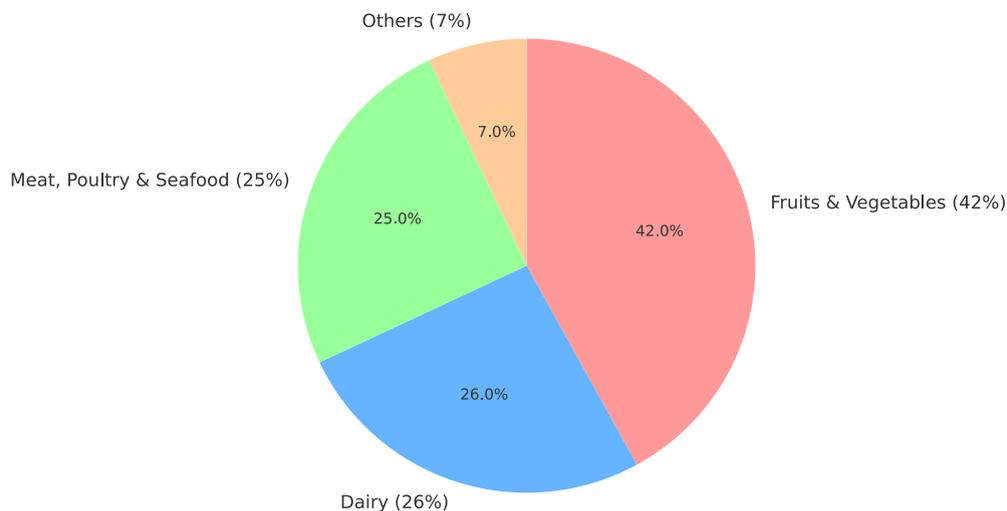


FIGURE 1.3: Distribution of food categories by perishability [48, 250]

- **Dairy Products:** Such as milk, cheese, yogurt, and cream are highly sensitive to microbial contamination and must be kept at constant refrigeration temperatures. These products have relatively short shelf lives and are vulnerable to spoilage from temperature fluctuations which need to strict hygiene, cold chain management, and compliance with safety standards to ensure their quality and safety [258].
- **Meat, Poultry and Seafood Products:** These products are highly perishable due to their susceptibility to bacterial growth, and toxins[262]. The risk in this type of food

require strict temperature control and hygiene at every stage of the supply chain with advanced preservation technologies, such as ice-packed transport or modified atmosphere packaging [49, 287].

To maintain the safety and quality of these food types, it must be handled quickly and stored under controlled environments, such as refrigeration or freezing, and follow them in real time for protection. Any delay or deviation in control of environmental conditions can result in spoilage, contamination, or loss of nutritional value.

Multi-Stages and Multi-Actors Structure

A defining feature of the food supply chain is its multi-stage, multi-actor structure, reflecting the complexity and interdependence of various processes [16, 251]. This diversity of stakeholders and steps often leads to decentralized decision-making and fragmented information systems, resulting in inefficiencies, data silos, and making coordination and transparency significant challenges [10]. Figure 1.4 illustrates the complete food supply chain process, outlining its main stages and the actors involved at each step.

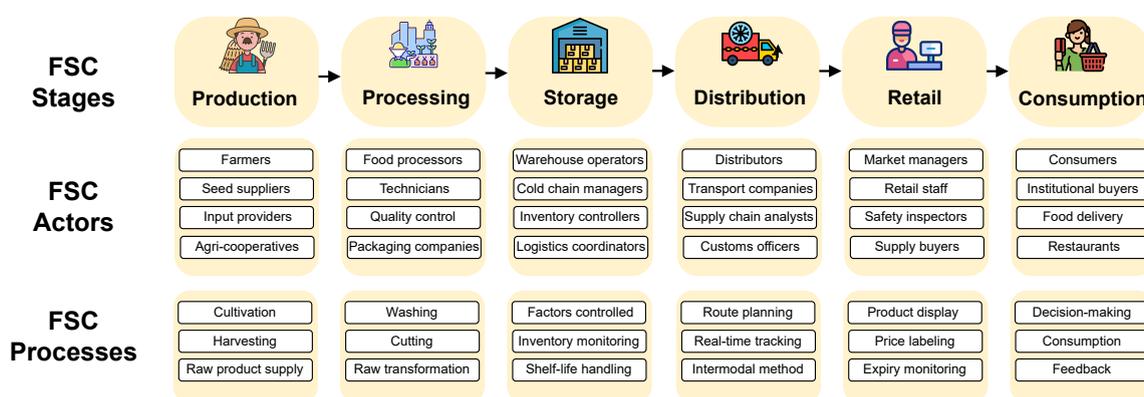


FIGURE 1.4: Food supply chain main stages, actors and processes

The FSC comprises multiple stages, including agricultural production, food processing, packaging, storage, transportation, wholesale, retail, and final consumption [226]. Each of these stages involves different actors such as farmers, input suppliers, processors, logistics providers, regulatory bodies, retailers, and consumers, who all contribute to the transformation and movement of food products along the chain [103, 480]. The main phases and stages characterized by the food supply chain are described below:

- **Production:** This is the initial stage of the food supply chain, where raw food materials are produced through crop cultivation, livestock farming, and aquaculture to generate primary food products that will later be processed or consumed. This stage is highly dependent on natural resources, climate conditions, and agricultural practices, and involves various actors such as farmers, agricultural cooperatives, seed and fertilizer suppliers, and livestock breeders [136].
- **Processing:** The second stage, processing and manufacturing, transforms raw agricultural products into consumable food. This includes activities such as washing, cutting, and

packaging, carried out by various actors, including food processors, quality control bodies, and technicians. This stage adds value, enhances safety, and extends shelf life, while ensuring compliance with hygiene and food safety standards [201].

- **Storage:** This step involves warehouse managers, cold chain operators, logistics providers holding processed food under specific environmental conditions like ambient, refrigerated, or frozen to maintain its safety and quality before it is distributed to consumers. This stage presents challenges related to energy use, cost, and infrastructure limitations, especially in rural or developing areas [48].
- **Distribution:** In this stage, food products are transported between farms, processing facilities, warehouses, retailers, and ultimately to end consumers across long distances, including international routes using road, rail, air, or sea. This stage often integrates technologies such as GPS tracking, IoT sensors, and RFID tags to enable real-time monitoring and visibility [385]. Packaging is also a key component of this stage, providing protection during transit and ensuring compliance with domestic and international regulations for cross-border shipments.
- **Retail:** The retail stage is where food products become available for purchase by businesses or directly by end consumers which is responsible for the final display, labeling, and maintenance of food quality prior to purchase. Retailers also play a vital role in consumer education and building trust, often through the use of product certifications, origin labeling, and QR codes that provide traceability and additional product information [309].
- **Consumption:** The consumption stage in the food supply chain refers to the use of food by individuals or institutions such as households, restaurants, schools, and hospitals. At this point, consumer preferences, cultural practices, health awareness, and dietary needs strongly influence purchasing and usage patterns [207, 457].

Understanding the multi-stage, multi-actor nature of the food supply chain is critical to identifying vulnerabilities and designing technology interventions that enhance coordination, transparency, and trust among stakeholders.

Sensitivity to Environmental and Temporal Factors

One of the most critical features of the food supply chain is its high sensitivity to external that directly impact yields, harvest schedules, and overall food availability [111]. Unlike other types of supply chains, food systems rely heavily on stable environmental conditions and precise timing across all stages, from agricultural production to final consumption. Many factors affect the food supply chain process, each originating from different sources and requiring specific management approaches. Therefore, effectively managing these factors is essential to ensuring the reliability, safety, and sustainability of food supply chains. The most influential factors impacting the FSC across all stages and stakeholders can be classified into environmental and temporal categories.

Environmental factors

Environmental factors refer to natural conditions and ecological elements that influence the behavior and outcomes of the food supply chain at all stages from production to consumption [67]. These factors threaten the stability and safety of the FSC and pose major challenges

such as reduced crop yield, contamination, and food spoilage. Due to their nature, managing environmental risks requires real-time monitoring, adaptive strategies, and robust infrastructure. Key environmental factors include:

1. **Temperature:** Temperature plays a critical role in the integrity and efficiency of the food supply chain, particularly for perishable goods which can cause immediate spoilage, reduce shelf life, and accelerate microbial growth, while low temperatures can damage certain crops and freeze-sensitive products [349]. These risks are especially relevant during transportation and storage stages, where maintaining the cold chain is vital and even short-term exposure to unsuitable temperatures can result in product rejection, waste, or health risks for consumers [14, 274].
2. **Humidity:** Humidity is also an important factor for food products at all stages of the supply chain, which needs to be well managed to prevent the growth of mold and bacteria, while too low humidity can dry out or spoil products such as fruits and grains [196].
3. **Rainfall and Drought:** Rainfall plays a crucial role in supporting crop growth and overall agricultural productivity. However, its variability, whether abundant or scarce, can significantly impact the reliability and efficiency of food supply chains [93].
4. **Soil Quality:** Soil health is essential for food production, and its degradation poses a serious threat to the supply chain, including nutrient depletion, salinization, and contamination with chemicals or heavy metals [387]. Poor soil conditions lead to reduced nutritional quality and increased costs for fertilizers and soil treatments, which can impact the entire supply chain, causing resource shortages, reduced profitability, and increased market volatility [47, 275].

Temporal factors

Temporal factors refer to time-based conditions and constraints related to the planning, movement, and shelf life of food products within the supply chain. These factors pose significant challenges, such as product spoilage, poor inventory management, and mismatched supply and demand cycles, and play a critical role in determining product availability and reducing food waste [216]. Key temporal factors include:

1. **Seasonality:** It is associated with major disruptions such as droughts, floods, and heat waves, which compromise the stability and reliability of food systems [121, 255]. These disruptions often introduce uncertainty into planting and harvesting cycles, forcing producers and supply chain managers to adapt to increasingly unpredictable conditions. Without effective adaptation, these impacts can lead to reduced food availability, higher prices, and increased volatility in global markets [354]. In response, stakeholders are increasingly investing in climate-resilient agricultural practices [135], early warning systems [399], and adaptive infrastructure [22] to mitigate these risks and enhance long-term supply chain resilience.
2. **Harvesting Schedules:** Harvesting time is a key factor at the production stage, determining when products enter the supply chain. Proper scheduling ensures alignment with processing, storage, and distribution activities, maintaining product quality and minimizing losses [389].

3. **Shelf Life:** Shelf life defines the period during which food remains safe and retains its desired quality. It influences storage, handling, and distribution decisions across the supply chain, requiring precise timing and temperature control [291].
4. **Lead Time:** Lead time refers to the duration between ordering and receiving food products across different supply chain stages. It is a key factor influencing coordination, inventory planning, and maintaining food safety and freshness [285].
5. **Market Timing:** Market timing involves synchronizing food availability with consumer demand periods, such as holidays or seasonal trends. Effective timing supports optimal sales, reduces excess inventory, and aligns production with consumption patterns [106].

The sensitivity of the food supply chain to environmental and temporal factors makes it particularly vulnerable to various disruptions, with each factor requiring tailored management strategies to maintain product quality, safety, and availability. Since these factors are time-sensitive, any delay at any stage can have big effects. Therefore, resilience, proactive risk planning, and technological interventions (such as the internet of things, climate-resilient infrastructure, and smart logistics) are critical to building a robust and sustainable agricultural supply chain [29].

1.2.4 Architecture

The architecture of the food supply chain is composed of multiple interconnected layers that represent the essential flows required to support food production, distribution, monitoring, and exchange. It includes the physical layer, which manages the movement of goods; the information layer, responsible for data collection using appropriate technologies; the data management layer, which handles data processing and transforms it into actionable insights; and the application or presentation layer, which facilitates user interaction. Moreover, this layered architecture must support critical information flows such as product traceability, quality assurance, regulatory compliance, and demand forecasting to ensure efficiency and transparency throughout the supply chain.

The food supply chain architecture can be viewed as a linear or circular system, depending on the supply chain model. In a traditional linear model, goods flow in one direction, while in a modern, sustainability-focused architecture, the system may include reverse flows for returns, waste management, recycling, or reprocessing [184]. Figure 1.5 illustrates the layered architecture of the food supply chain, highlighting the interactions between the layers.

Physical Layer

The physical layer of the food supply chain architecture focuses on the real-world infrastructure and technologies used to capture and monitor critical data throughout the supply chain [297]. This layer integrates IoT sensors, RFID tags, GPS, and other smart sensing devices that continuously gather information related to product location, temperature, humidity, handling conditions, and storage environments [116]. These physical components are embedded at various stages from production fields and processing plants to transport vehicles and retail shelves to ensure real-time monitoring and early detection of potential risks [339].

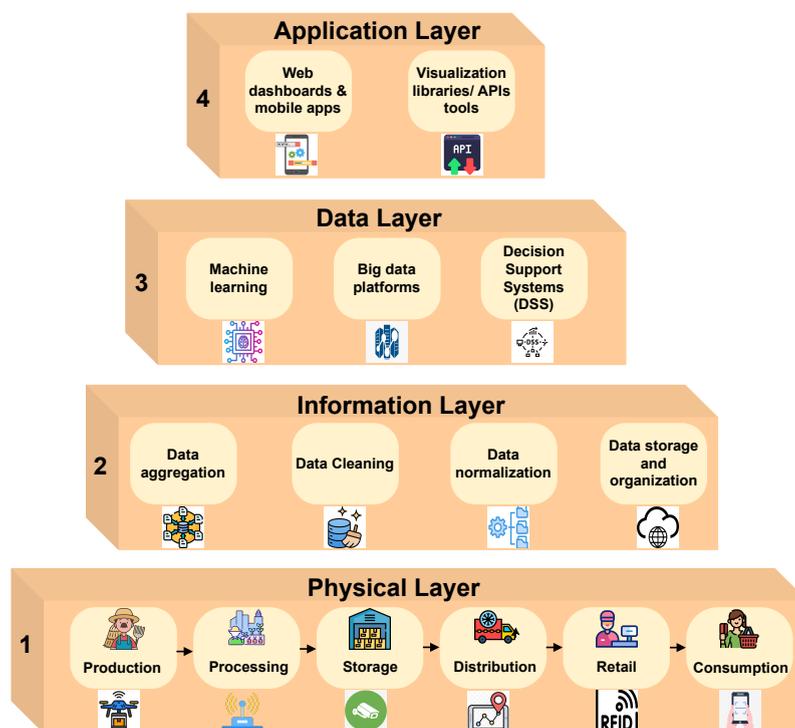


FIGURE 1.5: Food supply chain architecture

Information Layer

The information layer is responsible for transforming the raw heterogeneous data collected from the physical layer into usable information. This layer performs essential functions such as data aggregation, cleaning, normalization, storage, and organization, ensuring that the data is accurate, consistent, and ready for analysis or query [469]. It supports the use of databases, cloud storage platforms, and middleware systems that facilitate efficient data flow across various stakeholders [183, 358]. Ensuring data integrity, availability, and security at this stage is critical, as this information forms the basis for traceability, compliance monitoring, and decision-making in subsequent layers.

Data Analytics Layer

This layer is dedicated to extracting information by leveraging advanced analytical techniques such as descriptive, predictive, and prescriptive analytics to enable informed operational and strategic decision-making [27]. It supports critical functions including risk assessment, anomaly detection, and the evaluation of sustainability metrics such as carbon footprint and food loss rates. This enhances supply chain agility and responsiveness by enabling stakeholders to anticipate disruptions, improve resource allocation, and optimize logistics. Technologies such as machine learning algorithms, data visualization platforms, and decision support systems (DSS) are often employed to make complex data more interpretable and actionable [350].

Application and Presentation Layer

The Application and Presentation Layer serves as the interface between the food supply chain system and its end users, allowing actors to interact with data, visualize insights, and execute informed decisions [394]. This layer includes user-facing tools such as dashboards, reporting systems, traceability platforms, and mobile or web applications designed to present complex information in a clear format. It plays a crucial role in ensuring transparency and usability, allowing consumers and other actors to access relevant data and monitor supply chain performance [68].

1.3 Food Safety Concept in Food Supply Chain

Following the overview of the food supply chain's structure, features, and architecture, it is essential to address one of the most critical aspects of this system which is the food safety. Ensuring the safety of food products throughout their journey is fundamental to protecting public health, maintaining consumer trust, and complying with regulatory standards. This section explores the concept of food safety within the context of the food supply chain, highlighting its importance, the risks and challenges it faces at different stages, and the techniques used to manage these issues.

1.3.1 Definition

Food safety has been a concern for centuries, with early civilizations implementing preservation techniques such as drying, salting, and fermenting to prevent foodborne illnesses [138]. As societies advanced, formal food safety regulations began to emerge most notably with the Pure Food and Drug Act (1906) in the United States, and the establishment of the Codex Alimentarius (1963) by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) to standardize global food safety practices [122, 431].

- The FAO defines food safety as:

"The absence or acceptable levels of hazards in food that may harm the health of consumers. Hazards can be biological, chemical, or physical in nature."

— FAO, *Food Safety and Quality* [344]

- A complementary definition provided by the Codex Alimentarius emphasizes the techniques and measures involved:

"Food safety encompasses all measures taken to ensure that food is safe for consumption, including hygiene practices, control of food hazards, and application of international standards and regulations."

— CA, *General Principles of Food Hygiene* [117]

- According to the organization definitions, we define the food safety in the food supply chain as:

"A condition in which all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life."

Based on these definitions, the concept of food safety can be summarized through four essential pillars: Availability, Accessibility, Stability, and Utilization [66]. These pillars work together to ensure that food remains safe, nutritious, and accessible to all consumers, as illustrated in Figure 1.6.

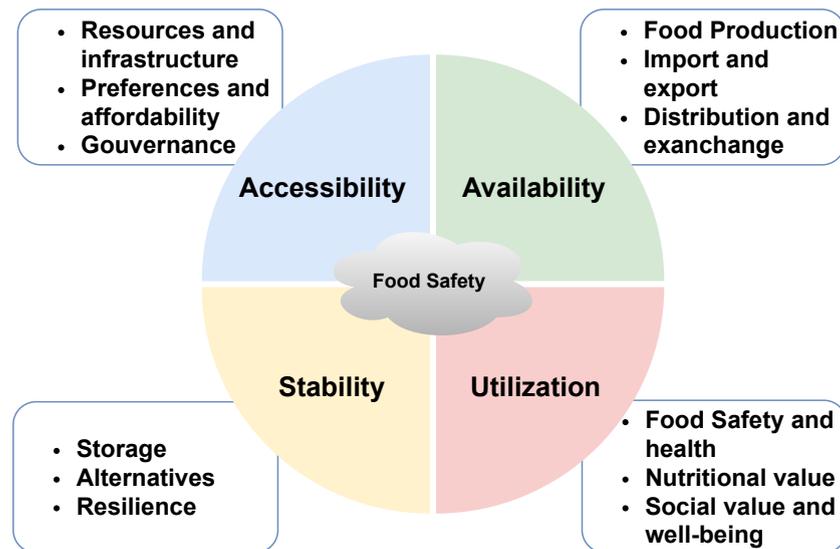


FIGURE 1.6: Four pillars of food safety concept [66]

1. **Availability:** This point ensures that food products are consistently present in adequate quantities and of good quality. It depends on domestic production, food importation, and proper distribution mechanisms [308].
2. **Accessibility:** Refers to the presence of infrastructure, such as roads, water transport, and physical stores, as well as economic factors that enable consumers to purchase food at an affordable and stable price [120].
3. **Stability:** Involves managing various factors that affect food production, including price fluctuations, organizational collaboration, food inspections, and population growth. External factors such as geopolitical tensions, climate change, and natural disasters also play a significant role to ensure this factor [127].
4. **Utilization:** Ensures that food consumption meets health and nutritional needs. It is influenced by consumer knowledge about food choices, eating habits, knowledge of nutrients, food preparation methods, and hygiene conditions [2].

1.3.2 Risks and Hazards

There are different sources and types of hazards associated with the safety of food products, which can emerge and propagate across all stages of the supply chain. These hazards are generally classified into three major categories and leads to many problems and concerns in the food supply chain process and need to specific management [407]. Figure 1.7 define the different food safety risks and hazards in the food supply chain process.

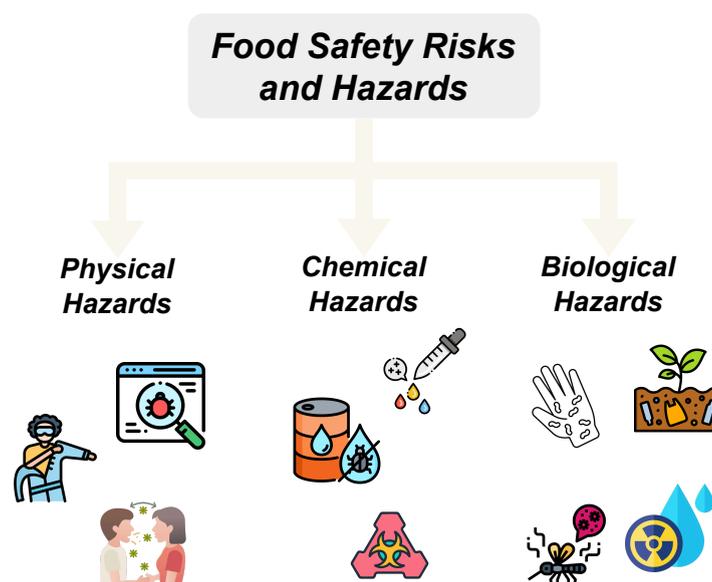


FIGURE 1.7: Risks and hazards affected food safety in food supply chain

Biological

Biological hazards are microorganisms that can cause foodborne illnesses such as bacteria (e.g., *Salmonella*, *Listeria*), viruses (e.g., Norovirus, Hepatitis A), parasites (e.g., *Giardia*, *Trichinella*), and molds or their toxins [345]. These hazards often arise from contaminated water, soil, animals, or improper handling and storage during food processing and transportation [408].

- **Sources:** Contaminated water, soil, infected animals, unhygienic handling, and cross-contamination during processing or packaging.
- **Impact:** These hazards cause foodborne illnesses, leading to gastrointestinal disorders, hospitalization, and even death, especially in vulnerable populations.
- **Stage of Risk:** Occurs primary during the stages of production, processing and food preparation.

Chemical

Chemical hazards refer to harmful substances that can enter the food chain through agricultural practices, food processing, or environmental contamination that can pose chronic health risks [386]. These include pesticide residues, food additives, veterinary drug residues, and naturally occurring toxins.

- **Sources:** Agricultural inputs, industrial pollution, unregulated processing methods, and inadequate residue monitoring.
- **Impact:** Chronic exposure can lead to cancer, neurological disorders, reproductive issues, or acute poisoning.
- **Stage of Risk:** Mostly occurs during agricultural production, processing, and packaging, but can also affect the storage and distribution phases due to migration of chemicals from packaging materials or environmental exposure.

Physical

Physical hazards are foreign objects or materials that may accidentally enter food products and cause health issues when consumed, such as equipment failure, poor handling practices, or contamination during production and packaging processes [295].

- **Sources:** Improper handling, inadequate quality control mechanisms, equipment malfunctions, or inadequate personnel training during food preparation and packaging.
- **Impact:** Physical hazards can lead to system-level failures in safety assurance processes, compromise data integrity in traceability systems, and trigger alerts in real-time monitoring platforms for contamination detection.
- **Stage of Risk:** Occurs primarily during the processing, packaging, storage, and final preparation of food.

1.3.3 Problems

Food safety issues stem from various sources of risks and hazards, as described in the previous section. These risks threaten the four fundamental pillars of food safety: availability, accessibility, stability, and utilization which not only impact urban food systems but also disrupt global supply chains, undermining the overall food safety framework. To better understand the safety problems related to the food supply chain, we propose a new taxonomy that categorizes these issues across three key dimensions: related to product types, related to consumer restrictions, and related to supply chain stages, as illustrated in Figure 1.8.

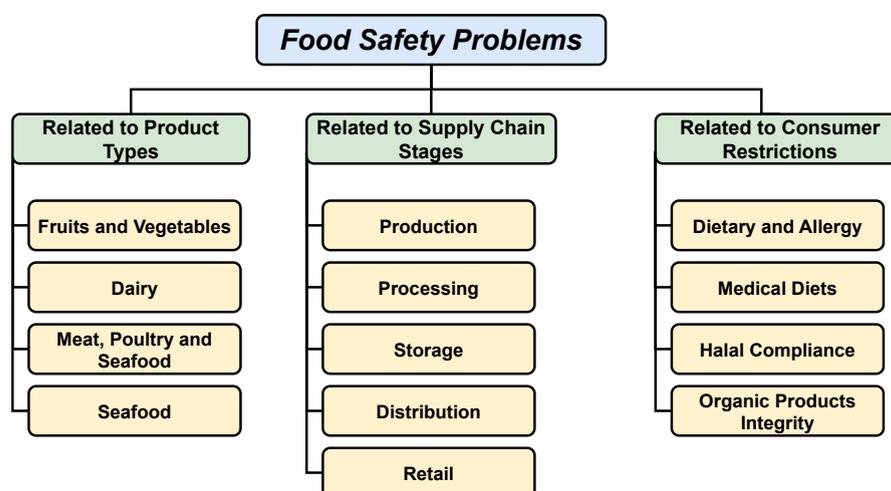


FIGURE 1.8: Food safety problems in food supply chain

Related to Products Types

Different types of food products pose distinct safety problems and are vulnerable to specific sources of risk such as biological, chemical, or physical across its lifecycle and need to a particular management. We analyze food safety problems associated with fruits and vegetables, dairy and meat products, and explore the various food safety issues for each type.

1. **Fruits and Vegetables:** Fruits and vegetables are essential components of a healthy diet, but are particularly susceptible to many problems in terms of food safety due to their high moisture content, biological nature, and often minimal processing [155, 400]. The safety problems of these products include:
 - They are often consumed raw or with minimal cooking, increasing the risk of exposure to harmful contaminants if proper hygiene and safety measures are not observed.
 - Their high perishability, coupled with frequent exposure to environmental conditions and human handling throughout the supply chain, makes them susceptible to microbial growth and spoilage.
 - They are prone to contamination from multiple sources, including soil, irrigation water, handling equipment, packaging materials, and transportation systems.
2. **Meat, Poultry and Seafood:** Meat, poultry and seafood products are particularly prone to safety problems due to their rich nutrient content and extensive handling requirements. Due to their complex composition and intensive handling throughout the supply chain, meat safety requires strict hygiene practices, cold chain maintenance, and monitoring of both biological and chemical hazards [171]. The safety problems of these products include:
 - Their high protein and moisture content creates an ideal environment for microbial growth, including pathogens such as *Listeria monocytogenes*, and *E. coli*, especially in the absence of proper hygiene practices.
 - These products are extremely sensitive to temperature variations and any failure in maintaining the cold chain during storage or transportation can lead to rapid spoilage and increased risk of foodborne illness.
 - These products may also contain chemical hazards, such as veterinary drug residues or contaminants introduced during processing, which pose chronic health risks if not effectively monitored and controlled.
3. **Dairy:** Dairy Products are highly vulnerable to food safety risks due to their biological characteristics, and sensitivity to transport and storage conditions. Given their complex global supply chains and high perishability, ensuring dairy safety requires efficient control systems of different types of risks across all stages [221]. The safety problems of dairy products include:
 - Contamination with pathogenic microorganisms such as *Listeria monocytogenes*, *Salmonella*, and *Escherichia coli* due to improper milking, handling, or processing practices.
 - Rapid microbial spoilage if the cold chain is broken during transportation, storage, or distribution, leading to souring and curdling.
 - Residues of veterinary drugs or antibiotics in milk from untreated or improperly managed dairy animals.
 - Chemical contamination from cleaning agents, pesticides, or environmental pollutants during production and processing stages.
 - Cross-contamination risks in shared equipment or facilities if sanitation protocols are inadequate.

In general, food safety risks related to each category of food products require specific monitoring and control protocols to ensure safety throughout the supply chain.

Related to Supply Chain Stages

Based on the types of food products discussed in the previous section, it is evident that food safety problems can arise at every stage of the supply chain. Each stage requires specific safety practices and preventive measures to preserve product integrity and protect consumer health [41]. In the following, we examine the key food safety issues associated with each stage of the supply chain, from production to consumption.

1. **Production Stage:** At this stage, chemical hazards, poor hygiene practices among frameworks, and inadequate disease management in livestock can compromise food safety, posing significant public health problems [224].
2. **Processing and Manufacturing Stage:** At this stage, various treatments on food products may introduce some problems such as cross-contamination between raw and processed products, inadequate temperature control, and chemical contamination resulting from the improper use of food additives which can negatively impact food safety [257].
3. **Storage Stage:** Inappropriate storage conditions, such as incorrect temperature, humidity, or ventilation, can accelerate spoilage and promote the growth of bacteria or mold, particularly in perishable products [132].
4. **Transportation Stage:** Lack of cold chain monitoring, delays, or poor vehicle sanitation may expose food to temperature abuse or contamination, especially in long-distance or cross-border supply chains [376].
5. **Retail Stage:** At the retail stage, food safety problems arise from improper labeling, and storage. Additionally, expired or mislabeled products can reach consumers if inventory is poorly managed [182].

Among all stages, the consumption stage typically reflects the least food safety risks, while storage and transportation are among the most critical, accounting for approximately one-fourth of the attention in food supply chain studies. These stages present higher food safety problems, which is why current research is primarily directed toward improving safety protocols in these stages.

Related to Consumers Needs

Food safety problems are influenced not only by product characteristics or supply chain stages but also by consumer-specific restrictions [244]. These restrictions may be medical, cultural, or dietary in nature, and failure to address them can pose significant health and ethical risks [444]. Understanding consumer restrictions is essential for accurately meeting consumer needs and ensuring food safety for all individuals, particularly those with dietary conditions such as celiac disease or diabetes [95, 247, 329]. Various types of consumer restrictions exist, each presenting problems that directly impact food safety management.

1. **Dietary and Allergy Restrictions:** Consumers with food allergies (e.g., to nuts or dairy) or intolerances (e.g., lactose or gluten) face serious health risks such as allergic reactions or digestive problems if food is improperly handled or if shared processing equipment leads to cross-contamination [179].

2. **Medical Diets:** Individuals with specific medical conditions, such as celiac disease require strict dietary controls. Mislabeling or the presence of trace allergens (e.g., gluten in gluten-free foods) can result in significant health complications [190].
3. **Halal Compliance:** For Muslim consumers, adherence to halal standards is essential which cross-contamination with non-halal ingredients or lack of transparency in sourcing and preparation can compromise food safety [382].
4. **Organic Product Integrity:** Consumers choosing organic foods expect products free from synthetic chemicals and genetically modified ingredients. False labeling or poor traceability systems can result in false consumption of non-organic substances, violating both safety and ethical expectations [110].

Effectively addressing food safety challenges associated with consumer restrictions expands the scope of food safety in the industry and ensures that all individuals, regardless of their dietary requirements, have access to safe and properly regulated food products.

1.3.4 Mechanisms

Maintaining food safety in the food supply chain demands proactive strategies and specialized techniques designed to reduce safety risks across various food products, supply chain stages, and consumer-specific restrictions. These mechanisms are further supported by digital technologies that facilitate automation, data logging, and predictive analysis, thereby enhancing the efficiency, transparency, and accountability of food safety management [398, 443]. In the following sections, we classify food safety mechanisms into three main categories: Traceability, Real-time Monitoring, and Data-Driven Decision Making. Each key mechanism is presented along with its primary sub-applications, highlighting its operational value and contribution to overall food safety assurance (see Figure 1.9).

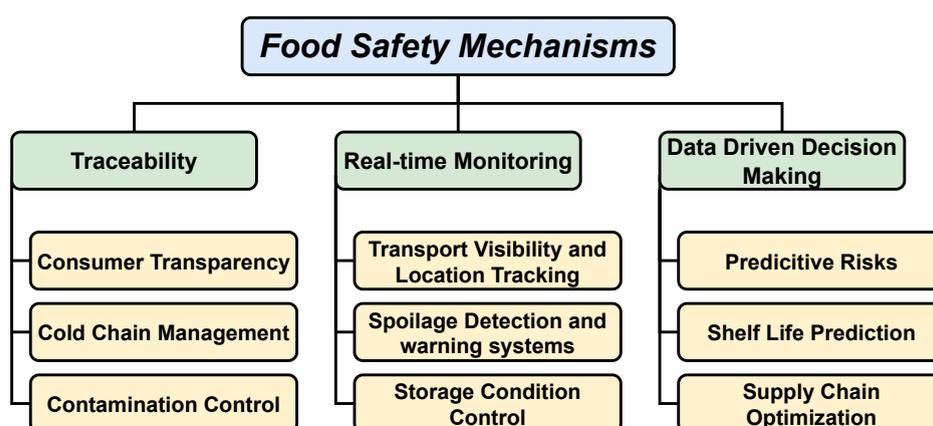


FIGURE 1.9: Food safety mechanisms in food supply chain

Traceability

Traceability is a foundational component of modern food safety management in the food supply chain. It enables the identification and documentation of the origin, journey, and transformation of food products and their ingredients across all stages from raw material sourcing to the point

of consumption [75]. Additionally, this technique rely on various technologies such as barcodes, QR codes, and RFID tags to record data at each transaction or processing point in complex food supply chains which enhances transparency, accountability, and consumer trust, while reducing response time to safety incidents [397, 429].

Traceability systems support two types of traceability (see Figure 1.10 and Table 1.3):

- **Forward Traceability (Tracking):** Monitoring the movement of food from production to end consumption.
- **Backward Traceability (Tracing):** Tracing food products from the point of sale back to their origin.

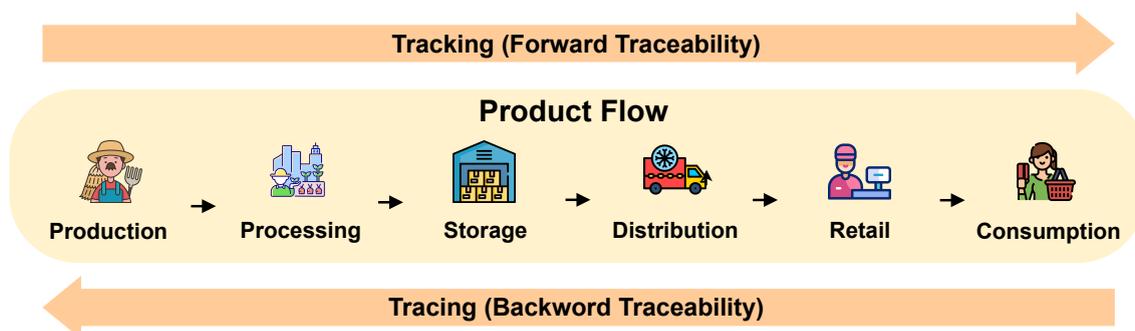


FIGURE 1.10: Visual representation of tracking and tracing traceability processes

Traceability Type	Technologies Used	Food Safety Problems Addressed	Advantages
Tracking	Barcodes, QR codes, RFID tags, GPS, IoT sensors	Product spoilage during transport, cold chain breaks, delays, inventory mismanagement	Enables real-time monitoring, improves logistics, allows faster recalls
Tracing	Cloud computing, databases, barcodes, data logs	Unknown origin of contamination, fraudulent labeling, allergen misidentification, food fraud	Ensures source verification, supports audits, increases consumer trust

TABLE 1.3: Comparative analysis of tracing and tracking techniques in food supply chain [75, 429]

1. **Consumer Traceability:** Traceability systems with two mechanisms tracing and tracking support consumer access to verified information about the origin, journey, and quality of food products to improve consumer confidence and encourage ethical consumption. For example, the system proposed in [365] develops a traceability prototype based on cloud computing technology to enhance consumer trust by ensuring transparency in food product histories. Similarly, the study in [58] emphasizes that electronic traceability systems improve consumer confidence and transparency by providing detailed information about meat production, including the animal's life history and internal industry processes, thereby fostering trust in food quality and safety. Additionally, the system in [19] offers traceability of environmental conditions in the food supply chain. By combining IoT devices and distributed databases, it captures detailed carbon emissions data across various stages, ensuring transparency, privacy, and collaboration among supply chain participants.

2. **Cold Chain Management:** The traceability technique is integrated into cold chain management by recording temperature data and other environmental conditions at every stage and location of the supply chain [45]. Technologies such as RFID sensors and Internet of Things (IoT) devices enable real-time tracking of transportation and storage conditions [165]. Any deviations from the required parameters can be immediately traced back to the responsible stage, allowing for rapid intervention and minimizing the risk of spoilage or food safety incidents. Many systems have been developed in this domain to ensure effective cold chain management and traceability throughout the logistics network. For example, [377] proposed a traceability platform designed to enable better monitoring of food products throughout transportation, thereby minimizing safety hazards and reducing food spoilage. Similarly, the work in [81] presents a cold chain traceability system that leverages (IoT) technology to monitor logistics processes by captures key data such as ambient temperature, humidity, and geographic location, which are stored locally and transmitted to a cloud-based data service platform.
3. **Contamination Control:** Traceability techniques are highly beneficial in contamination control, enabling stakeholders to isolate affected batches of food products, trace their path through the supply chain, and identify other products that may have been exposed. This facilitates faster and more targeted product recalls, thereby minimizing consumer risk. For instance, the system in [311] investigated the role of RFID in enhancing recall efficiency within perishable food supply networks by analyzing contamination recall dynamics under different visibility levels, highlighting the importance of granular tracking both upstream and downstream. Similarly, [86] proposed an improved safety system for tracking nuclear contamination in seafood by integrating wireless sensor networks (WSN) and RFID with blockchain technology. Their study demonstrated how this integration ensures real-time detection of contamination risks and secure data recording, enabling stakeholders to collectively manage and oversee food safety.

Sub-Application	Technologies Used	Food Safety Problems Addressed	Benefits & Advantages
Consumer Traceability [19, 58, 365]	Cloud computing, Distributed databases, IoT, QR codes	Lack of transparency, Food fraud prevention, Misinformation control, Unethical sourcing	Enhanced consumer trust, Supply chain transparency, Market credibility, Fraud prevention
Cold Chain Management [81, 377]	RFID sensors, IoT devices, GPS trackers, data platforms	Product spoilage, Temperature abuse, Cold chain failures, Environmental exposures	Real-time monitoring, Early spoilage detection, Regulatory compliance, Logistics efficiency, Reduced losses
Contamination Control [86, 311]	RFID technology, Wireless Sensor Networks, Traceability databases	Biological/chemical contamination, Inefficient recalls	Rapid targeted recalls, Source identification, Reduced health risks, Stakeholder accountability

TABLE 1.4: Comprehensive overview of traceability applications

Real-Time Monitoring

Monitoring technique throughout the food supply chain process plays a critical role in enhancing food safety by providing immediate and real time visibility into environmental and operational conditions that directly affect product quality and safety [1]. This technique involves the continuous collection, transmission, and analysis of data related to temperature, humidity, gas concentration, location, and other factors that influence the perishability and stability of food products [46]. Many latest food safety applications is based on this techniques with the integration of technologies like IoT, smart sensors, wireless communication networks, and cloud computing to detect anomalies instantly and take corrective actions before food quality is compromised [25, 419].

- 1. Transport Visibility and Location Tracking:** Distribution is a vulnerable stage in the food supply chain, particularly for perishable goods that require controlled conditions over long distances. Integrating GPS tracking systems with environmental IoT sensors enables continuous monitoring of both location and physical parameters during transit. These systems report real-time data such as truck position, temperature, humidity, shock/vibration, and door status to centralized platforms or cloud-based dashboards [410, 411]. With this level of visibility, it becomes possible to identify and respond promptly to food safety incidents such as route delays, mechanical failures, or temperature excursions [435]. For example, the system in [402] developed an IoT driven route planning system that integrates multi-temperature packaging, real-time environmental monitoring, and optimized delivery routes to effectively reduces food spoilage during transportation by maintaining optimal conditions tailored to different perishable products. Another work in [18] focuses on improving supply chain sustainability for small food businesses by incorporating biosensors and intelligent IoT modules for real-time detection of contamination and better management of transportation conditions.
- 2. Spoilage Detection and Early Warning Systems:** Beyond environmental monitoring, advanced real-time food safety systems integrate biosensors and chemical indicators to detect early signs of food degradation [364]. These sensors can identify the presence of volatile organic compounds, such as ammonia or sulfur compounds, which are emitted during bacterial growth or decomposition processes. Others monitor parameters like pH shifts, oxygen depletion, or the presence of specific microbial metabolites that are indicative of spoilage [271]. By implementing spoilage detection systems, supply chain stakeholders can take essential actions to intervene before compromised products reach consumers, thereby ensuring overall food safety. For instance, the system presented in [313] utilizes chemical sensors and biosensors to monitor milk quality by detecting spoilage indicators such as pH variation and oxygen concentration. Another system in [26], developed an intelligent sensor foil capable of detecting biogenic amines produced during the spoilage of animal-origin foods by changes the color in response to spoilage, with results measurable via spectroscopy or smartphone cameras. The solution integrates QR codes and distributed database to associate freshness data with individual food packages, promoting transparency and traceability.
- 3. Storage Condition Control:** Storage stage in the food supply chain are critical control points where inappropriate conditions can accelerate spoilage, reduce shelf life, and pose health risks [268]. Real-time monitoring technique for food safety have evolved to include smart sensors with smart techniques capable of continuously measuring a wide array of environmental parameters [9]. By managed the data collected and transmitted

in real time from the storage stage, these systems can detect deviations from optimal ranges of storage condition and automatically play a corrective actions, such as adjusting refrigeration settings, or issuing alerts to facility managers. For example, for fruits and vegetables products the system in [206] presents an IoT enabled sensor network designed for real-time monitoring of storage conditions in the supply chain. By employing machine learning algorithms, it ensures optimal storage conditions, thereby preserving the freshness and quality of products throughout the supply chain, ultimately enhancing safety and reducing losses. Another work in [202] monitors food quality in real time across the supply chain, including storage conditions with AI and IoT technologies. The system adapts to various environmental conditions, making it suitable for maintaining food quality during storage and throughout the supply chain.

Sub-Application	Technologies Used	Food Safety Problems Addressed	Advantages / Benefits
Transport Visibility & Location Tracking [18, 402]	IoT sensors, GPS trackers, Cloud platforms, Wireless networks	Loss of visibility, Temperature deviations, Transport delays, Shock damage	Enhanced transparency, Timely delivery assurance, Cold chain maintenance, Spoilage prevention
Spoilage Detection & Early Warning [26, 313]	Biosensors, Gas sensors, pH indicators, Smartphone apps	Microbial growth, Chemical spoilage, Gas release	Early intervention, Freshness improvement, Waste reduction
Storage Condition Control [202, 206]	Smart refrigeration, IoT sensors, Machine learning, Humidity/temperature monitors	Poor storage conditions, Conditions fluctuations, Reduced shelf life	Optimal maintenance, Product freshness extension, Operational cost reduction, Storage efficiency improvement

TABLE 1.5: Comprehensive overview of real-time monitoring applications

Data-Driven Decision Making

Data-driven decision making (DDDM) plays a vital role in the food supply chain, where vast amounts of data are require effective management to enhance food safety [205]. DDDM systems rely on digital technologies such as artificial intelligence (AI) and big data to enable stakeholders to access real-time data streams from farms, factories, warehouses, and retail environments. When analyzed through advanced analytics platforms, this data uncovers patterns, trends, and anomalies that help prevent food safety risks and enable efficient recall management [276]. Data-driven systems technique for food safety in food supply chain also empower food organizations by multiples actions to transition from reactive responses to predictive and prescriptive strategies, improving responsiveness, traceability, and consumer trust.

1. **Predictive Risk Assessment:** Predictive analytics identify and mitigate food safety hazards in the food supply chain before poses a problems [293]. By analyzing the big data collected from sensors, quality inspection reports, equipment logs, and environmental

conditions, the developed models can predict the likelihood of contamination or process failures [359]. For example, if there is an affection of microbial growth in production step, the predictive models can help to preventative disinfection protocols. The prediction systems can also integrate external data such as weather forecasts or supply chain delays to assess risks related to pests, spoilage, or cross-contamination during transportation [173]. The work in [21] utilizing advanced AI and machine learning tools to enhance predictive risk assessment in food supply chains, ensuring effective data-driven decision-making and improved food safety management. Another work in [149] introduces a data-driven multi-criteria decision-making method utilizing a transition decision tree algorithm, enhancing predictive risk assessment in food supply chains by analyzing risk factors and their interrelationships, guiding effective risk mitigation and contingency planning.

2. **Shelf Life Prediction:** Traditional shelf life estimation often uses static expiration dates that do not account for real-world variables [134]. DDDM enables dynamic shelf-life prediction by integrating continuous environmental monitoring (e.g., temperature, humidity, gas concentrations) within packaging or storage environments. These inputs feed into shelf-life prediction models that estimate remaining freshness based on actual storage conditions [87]. The work in [388] use computational models to anticipate microbial behavior under various storage and processing conditions. Techniques like one-step and two-step modeling, along with modern machine learning approaches, allow for high-precision estimation of microbial spoilage. Another work in [351] use the Artificial Intelligence (AI) and IoT sensors for real-time monitoring to improve spoilage estimation enabled predictive models that estimate spoilage more accurately by analyzing factors like temperature, humidity, microbial activity, and gas emissions.
3. **Supply Chain Optimization:** In traditional optimization systems, data collected from edge devices is often pre-processed and aggregated at local gateways before being transmitted to cloud systems, thereby reducing response time [175, 367]. Therefore, data analytics in the food supply chain enables the optimization of logistics to maintain safety standards and can adjust supply chain decisions by optimizing the logistics process [389]. For example, if delays are detected along a delivery route, a data-driven system can automatically reroute trucks to maintain cold chain integrity [74]. A case study of this technique is presented in Colombia [7], demonstrated significant cost savings and environmental benefits, with full route compliance and optimized vehicle usage. This model offers a sustainable solution for managing perishable food transportation, promoting efficient resource allocation and environmental conservation within the food supply chain. Another study in [428] predict and control food safety risks during the distribution of perishable foods by optimizing delivery routes to enhance cold chain efficiency and reduce costs. Additionally, using indexing techniques for data retrieval allows fast queries based on specific time windows and thresholds (e.g., identifying temperature breaches in the last 24 hours) [231, 335].

Sub-Application	Technologies Used	Food Safety Problems Addressed	Advantages / Benefits
Predictive Risk Assessment [21, 149, 173]	Predictive analytics, Big data platforms, Machine learning, IoT sensors, AI-based monitoring tools	Inability to detect early contamination, Unsafe storage conditions, Undetected hazards	Early hazard detection, Reduced foodborne risks, Proactive decision-making support, Improved safety compliance
Shelf Life Prediction [351, 388]	AI algorithms, Predictive microbiology, Real-time sensors (temperature/-gas/humidity), Spoilage models	Inaccurate expiration dates, Premature food spoilage, Excessive food waste	Improved freshness tracking, Dynamic shelf life estimation, Food waste reduction, Increased consumer trust
Supply Chain Optimization [7, 74, 428]	Big data analytics, Cold chain monitoring, Route optimization algorithms, Cloud computing, Indexing techniques	Delivery delays, Temperature abuse, Inefficient logistics, Slow traceability	Enhanced supply chain efficiency, Cold chain integrity assurance, Spoilage minimization, Cost reduction, Faster traceability

TABLE 1.6: Comprehensive overview of DDDM applications

1.4 Challenges and Research Gaps

Despite significant advances in food safety standards and the adoption of digital technologies, the food supply chain still faces persistent challenges due to its inherent complexity and the limitations of emerging technologies, which compromise transparency, traceability, and consumer trust (see Figure 1.11). The effective implementation of safe supply chain system in the food



FIGURE 1.11: Challenges of food safety in food supply chain

industry is hindered by several factors related to the nature of the FSC itself, which is composed of multiple challenges.

1. **Distributed and Multi-stage Structure:** The FSC involves numerous actors and processes spread across different geographical locations, requiring highly coordinated management.
2. **Coordination Complexity:** Synchronizing activities and information flow across all stages is difficult, leading to inefficiencies and gaps in oversight.
3. **Data Management Complexity:** Managing the vast amount of data generated across the FSC (e.g., sensor readings, transaction logs) requires robust data governance strategies.

While emerging technologies such as artificial intelligence, the internet of things, and big data offer promising solutions to these challenges, they are not yet sufficient to fully address the increasing complexity and evolving demands of modern food safety. In particular, food safety specific challenges continue to pose including:

1. **Privacy and Security Risks:** Food supply chains handle vast volumes of sensitive information, including supplier identities, food origin data, transportation logs, and quality control reports. Sharing this data across a distributed network increases the risk of data leaks, unauthorized access, and cyberattacks.
2. **Scalability and Data Integrity:** The food supply chain involves many transactions between many stages and actors per day, including real-time sensor readings, shipment records, and inspection data. Traditional food safety networks face scalability limitations due to low transaction throughput and high processing costs which leads to lack of real-time monitoring and limited traceability process of products.
3. **Interoperability and Standardization:** FSC relies on diverse digital systems, databases, and data formats without common data standards, creating significant issues of interoperability, making it difficult to exchange, compare, and aggregate data throughout the food supply chain. Additionally inconsistencies in labeling, tracking formats, and safety certifications limit the ability to achieve unified food safety techniques.

To overcome these limitations in the food supply chain, the adoption of high-performance technologies has emerged as a novel and transformative solution for decentralized data management, enhanced security, traceability, and ensuring food safety.

1.5 Conclusion

In conclusion, this chapter provides a comprehensive exploration of the food supply chain in the food industry, covering key aspects such as its definition, features, and architectural structure. It also examines critical food safety risks and issues, categorized by product types, consumer restrictions, and supply chain stages, and discusses essential food safety mechanisms and techniques, including traceability and tracking, real-time monitoring, and data-driven decision-making. Furthermore, the chapter includes a discussion of food safety challenges and future directions, highlighting the need for advanced solutions and setting the stage for the integration of emerging technologies. Overall, this chapter serves as a valuable resource for understanding the food supply chain and establishes a solid foundation for further research and innovation in the dynamic and evolving field of food safety.

CHAPTER 2

BLOCKCHAIN TECHNOLOGY: FUNDAMENTALS AND INTEGRATION IN FOOD SUPPLY CHAIN

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2.1 Introduction

After examining the food supply chain process and highlighting its main challenges related to food safety such as transparency and traceability, this chapter introduces blockchain technology as a new solution in the food industry, with a specific focus on its application to ensure food safety within the food supply chain. We begin by introducing blockchain technology and presenting its fundamental concepts, features, components, and architecture. Then we explore its applications across various sectors including finance, supply chain logistics, healthcare and energy, with a particular focus on how blockchain is being adopted in the food supply chain to enhance safety, accountability, and coordination. Although blockchain presents effective solutions for various use cases in this sector, several challenges and limitations must be studied, particularly concerning data management, scalability, and query efficiency.

2.2 Blockchain Technology Fundamentals

Given its growing influence and broad applications across various sectors, understanding the core components and their interactions has become essential. Blockchain represents a complex digital infrastructure comprised of multiple, tightly integrated components and multilayered architectures working together to address a wide range of challenges across diverse fields. A comprehensive study of these elements is essential to fully understand its potential and practical application.

2.2.1 History and Evolution

The core ideas behind blockchain technology emerged in the late 1980s and early 1990s when researchers Stuart Haber and W. Scott Stornetta proposed a cryptographically secured chain of blocks to ensure that document timestamps could not be tampered with [145]. In 1992, they improved the system by incorporating Merkle trees, which allowed multiple document certificates to be efficiently stored in a single block [98]. This early work formed the basic ideas behind blockchain technology, but it not widely used at the time. The history of blockchain technology evolved through several key stages as depicted in Table 2.1.

Period	Key Developments
Pre-Computer Era	<ul style="list-style-type: none"> • Traditional ledgers with manual recording of transactions • Physical bookkeeping systems prone to human errors
Late 20th Century	<ul style="list-style-type: none"> • Digital ledgers introduced electronic record-keeping • Centralized databases improved efficiency but created single points of failure
Late 20th–Early 21st Century	<ul style="list-style-type: none"> • Distributed digital ledger systems with network redundancy • Required trust among participating nodes in the system
Early 21st Century	<ul style="list-style-type: none"> • Decentralized ledgers enabled trustless transactions • Consensus mechanisms introduced, bringing scalability challenges
2008–Present	<ul style="list-style-type: none"> • Blockchain technology with cryptographic hash chains • Immutable blocks created new paradigms for trust and verification • Ongoing challenges with adoption and regulatory frameworks

TABLE 2.1: Blockchain technology evolution [164]

The modern concept of blockchain as a decentralized ledger was revolutionized in 2008 by the pseudonymous Satoshi Nakamoto, who published the Bitcoin whitepaper describing a peer-to-peer electronic cash system to secure transactions without a trusted third party, leading to the launch of Bitcoin in 2009 as the first practical blockchain application [286]. Since then, blockchain technology has undergone significant evolution, incorporating new functionality and progressing through several generations from Blockchain 1.0 to Blockchain 4.0 (see Figure 2.1) [84].

- **Blockchain 1.0:** Introduced decentralized transactions in cryptocurrency fields [12].
- **Blockchain 2.0:** Developed by Ethereum, expanded functionality with smart contracts and programmable agreements via Solidity [11].
- **Blockchain 3.0:** Improved scalability, interoperability, and energy efficiency, enabling a wider adoption through decentralized applications (Dapps) [252].
- **Blockchain 4.0:** Integrates with other technologies such as IoT, ICT in Industry 4.0 (e.g., supply chains, healthcare) to enhance data management and efficiency in industrial applications [57].
- **Blockchain 5.0:** It aims to support the Internet of Everything and future integration with Web 5.0 technologies.

2.2.2 Definition

Blockchain is a decentralized and distributed ledger that stores transaction data across multiple computers in a network in a way that ensures data integrity, transparency, and immutability

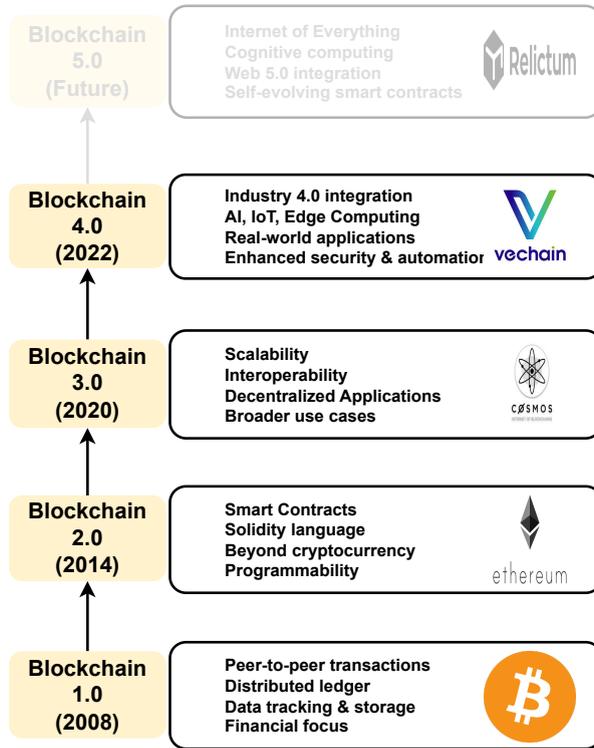


FIGURE 2.1: Blockchain technology generations

[253]. At its core, is a list of blocks that are cryptographically linked and secured using hash functions, and each block contains a batch of verified transactions, timestamp and the cryptographic hash of the previous block forming a secure and tamper-resistant chain of data (see Figure 2.2) [321].

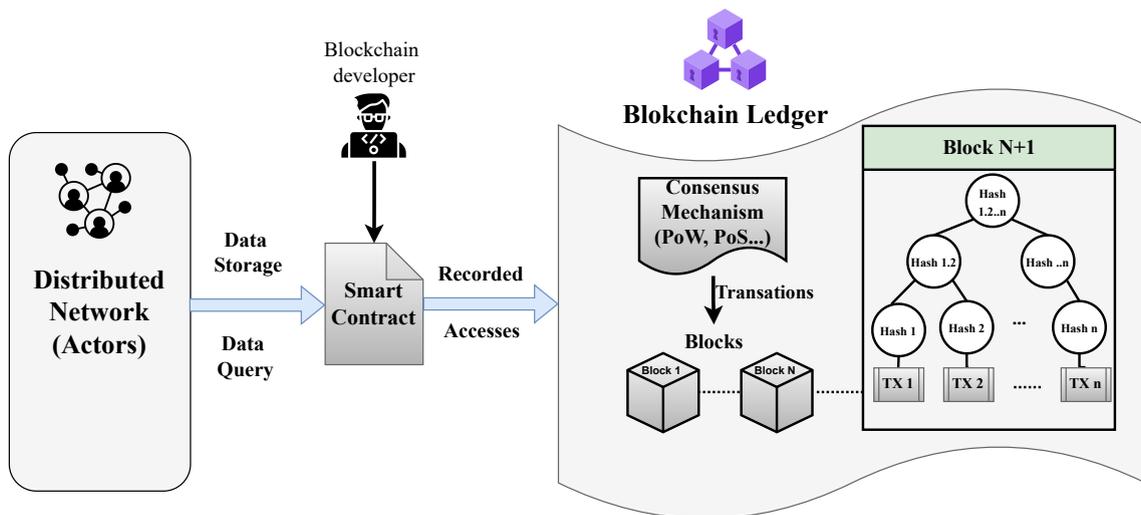


FIGURE 2.2: Blockchain technology overview

Other researchers, organizations, and standards bodies have defined blockchain technology in different ways, each focusing on different aspects of its structure and capabilities.

- According to its creator Satoshi Nakamoto (2008), blockchain is:

"A peer-to-peer distributed timestamp server that records transactions in chronological order and prevents double spending without relying on a trusted central authority."

— Nakamoto [286]

- The National Institute of Standards and Technology (NIST) defines blockchain as:

"Blockchains are distributed digital ledgers of cryptographically signed transactions that are grouped into blocks. Each block is cryptographically linked to the previous one (making it tamper evident) after validation and undergoing a consensus decision. As new blocks are added, older blocks become more difficult to modify (creating tamper resistance). New blocks are replicated across copies of the ledger within the network, and any conflicts are resolved automatically using established rules."

— NIST [446]

- Similarly, the World Economic Forum describes blockchain as:

"Blockchain can enable greater trust and transparency through decentralization, cryptography, and the creation of new incentives. Best-known as the digital underpinning of cryptocurrencies, it has evolved into a foundational technology with promise in many areas."

— WEF [430]

As a result, blockchain becomes an append-only data structure that leverages the benefits of multiple components and functions, making it a powerful tool for secure and verifiable data management across various sectors. This structure is implemented in well-known solutions such as Bitcoin [461], Ethereum [210], and Hyperledger Fabric [123].

2.2.3 Features

Following its definition, blockchain technology has attracted significant interest due to its numerous advantages derived from its core features. To fully understand these features, this section provides an overview of blockchain benefits such as transparency, security, decentralization, and data integrity as well as the main types of blockchain technology, including public, private, consortium, and hybrid models.

Benefits

Blockchain technology has rapidly gained attention across multiple sectors due to its unique combination of cryptographic security and decentralization, offering many benefits that enable it to overcome traditional limitations related to trust, transparency, and data integrity. The benefits of blockchain are described in the following section and illustrated in Figure 2.3.

1. **Decentralization:** Unlike traditional centralized systems that rely on a single authority, blockchain stores and control data across a peer-to-peer network of nodes and actors [462]. Each node holds a copy of the entire ledger and participates in the validation of transactions, ensuring that no single point of failure can compromise the system [209]. The

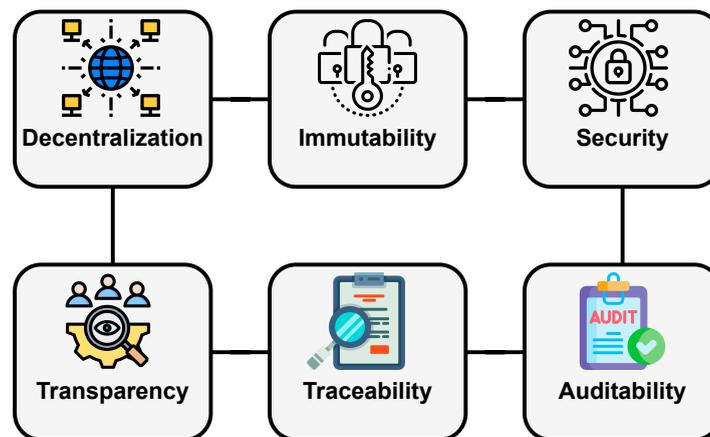


FIGURE 2.3: Blockchain technology benefits

main benefits of decentralization include improved system resilience, elimination of intermediaries, enhanced trust between participants, and greater resistance to manipulation [146].

2. **Immutability:** Immutability in blockchain is ensured by verifying each transaction before it is added to a block and once recorded, it cannot be modified or deleted [163]. Any attempt to tamper with the data would require altering all subsequent hashes, thereby disrupting the entire chain and making manipulation immediately detectable [296].
3. **Security:** Blockchain technology offer this benefit by eliminating centralized control or third-party intermediaries which guarantees that data transactions remains confidential and secure by encrypting all data and distributing it across a decentralized network using cryptographic techniques and digital signatures which only authorized parties can access the data using cryptographic keys . As a result, blockchain is often used in applications requiring high levels of trust and data protection [236].
4. **Transparency:** Transparency is one of the most important features of blockchain technology enables users and actors to view all changes to data and updates in real time [157]. The blockchain technology achieved this feature through the shared ledger that is accessible to all participants and all validated transactions are recorded on a ledger that is visible to all authorized participants and each modification must be approved by all participants, meaning that unauthorized changes, addition or deletions are visible [442].
5. **Traceability and Auditability:** Nodes within a blockchain system are empowered by these two features to track the complete journey of data and transactions throughout the network [253, 485]. Each record is timestamped and cryptographically linked to the previous one, allowing users to trace the origin, transformation, and movement of assets with precision [405]. Moreover, they ensure a transparent and verifiable history of all transactions, enhancing trust and regulatory compliance across the network [92].

Types

As blockchain technology continues to evolve, its applications have diversified to meet the needs of various industries and use cases [76]. Based on structure, access control, and governance mechanisms, blockchain systems are generally classified into two main categories: permissionless and permissioned (see Figure 2.4).

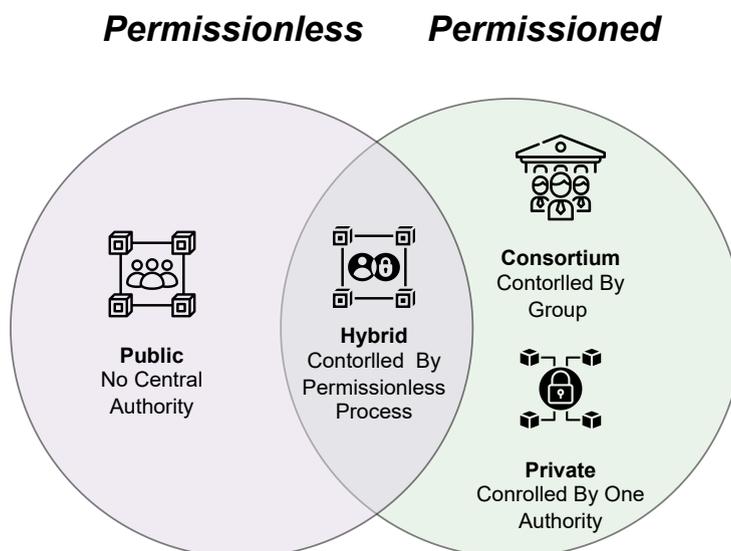


FIGURE 2.4: Blockchain technology types [316]

- **Permissionless Blockchains:** Allow anyone to join, validate transactions, and access data, offering high transparency and decentralization.
- **Permissioned Blockchains:** Restrict access to selected participants, providing greater control, privacy, and scalability for enterprise environments.

Within these categories, blockchain offers distinct features and advantages that make it suitable for specific operational and organizational needs. These features also guide the selection of an appropriate architecture based on factors such as transparency, scalability, privacy, and control, which determine how data is shared, who can participate in the network, and how compatibility and trust are maintained [4, 158]. Table 2.2 illustrates a comparison of the different types of blockchain.

Property	Public Blockchain	Consortium Blockchain	Private Blockchain
Consensus determination	All miners	Selected set of nodes	One organization
Read permission	Public	May be public or restricted	May be public or restricted
Immutability	Almost completely tamper-proof	Potential for tampering	Potential for tampering
Efficiency	Low	High	High
Centralized	No	Partial	Yes
Consensus process	Permissionless	Permissioned	Permissioned

TABLE 2.2: Comparative analysis of blockchain types [479]

1. **Public Blockchain:** Public Blockchains are fully decentralized and permissionless networks in which anyone can read, write, or validate transactions without prior authorization, making them completely transparent and open [64]. This type of blockchains are most commonly associated with cryptocurrencies such as Bitcoin and Ethereum, where trust is established through consensus mechanisms rather than relying on a central authority [403]. The primary advantages of public blockchains include high transparency and robust security but they often face challenges such as scalability issues and high energy consumption [189].
2. **Private Blockchain:** This type are managed by a single organization, and access to the network is limited to selected nodes whether for consensus participation or data viewing which enhances privacy, scalability, and operational efficiency [219]. Private blockchains offer many advantages, such as enhanced privacy, higher efficiency, faster transaction processing, and better scalability which make them particularly well-suited for enterprise use cases that require high performance such as financial services, supply chain management, and regulatory compliance [288]. However, these benefits come at the cost of decentralization, as control is concentrated within the managing organization [215]. Hyperledger Fabric, Multichain and Corda, are the most widely used platforms for private blockchains.
3. **Consortium Blockchain (Federated Blockchain):** Consortium Blockchains, also known as federated blockchains, represent a semi-decentralized model that acts as a compromise between public and private blockchains [100]. This collaborative structure allows multiple entities to share control over the blockchain network and only authorized participants can validate transactions, which significantly increases efficiency and speed compared to public and private blockchains [453]. Prominent examples of consortium blockchains include R3 Corda [208] that enable secure data exchange which are well-suited for controlled environments.
4. **Hybrid Blockchain:** Hybrid blockchains combine the strengths of both public and private blockchains, allowing organizations to manage which data are kept private and which data are shared publicly [181]. In this architecture, a private blockchain handles internal operations while a public blockchain provides verifiability and transparency for specific data. This dual-layer design allows organizations to maintain confidentiality over sensitive data while still leveraging the openness and trust making it a powerful choice for industries such as finance, healthcare, and government [234].

2.2.4 Architecture and Components

Blockchain technology operates through a layered architecture composed of multiple integrated components, with each layer responsible for specific functions that are essential to the system overall performance, security, and decentralization. The fundamental components that define the functionality of blockchain technology are grouped into four major layers: Data Layer, Network Layer, Consensus Layer, and Smart Contract Layer. Figure 2.5 illustrates the global architecture and the key components that constitute blockchain technology. These components are described in detail below.

Data Layer

The data layer in the blockchain system is responsible for storing and organizing data in the form of transactions and blocks within the blockchain immutable ledger based on techniques

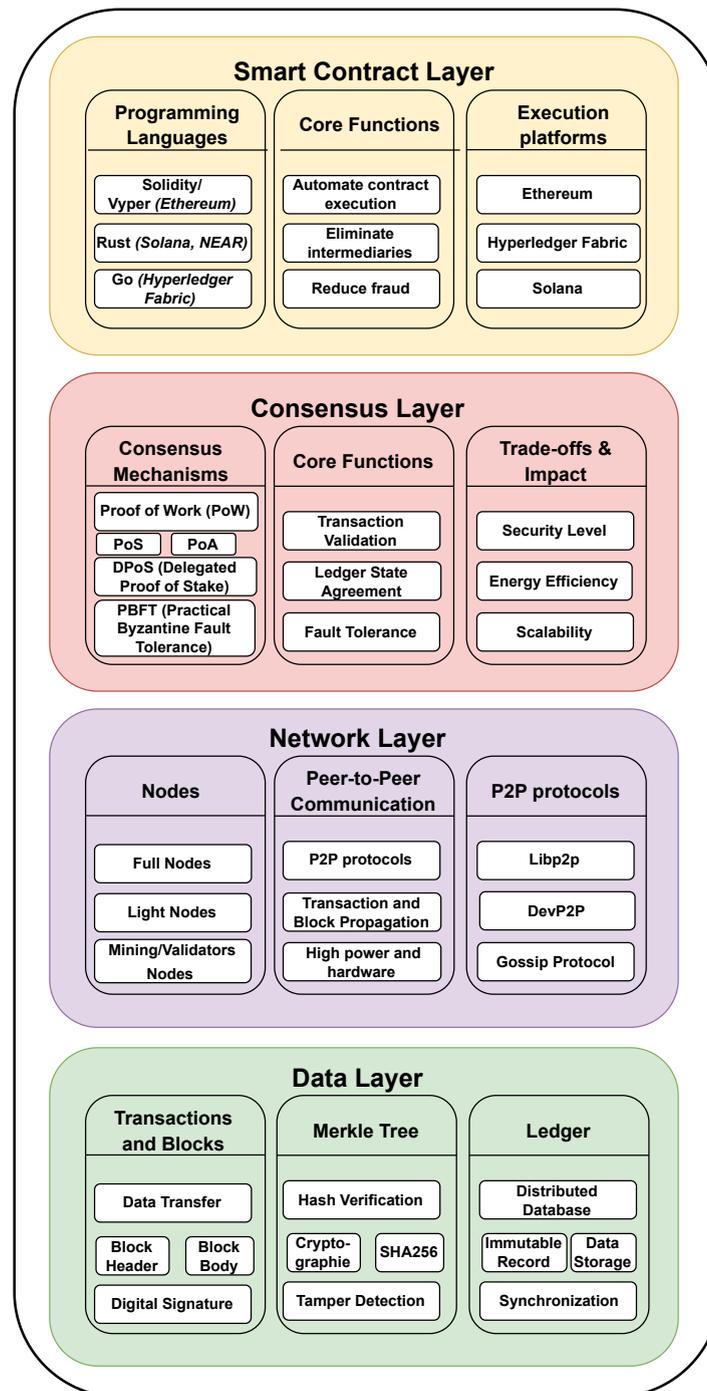


FIGURE 2.5: Blockchain technology architecture

such as block organization, transaction management, and Merkle tree-based data verification. Figure 2.6 represents the blockchain components in the data layer.

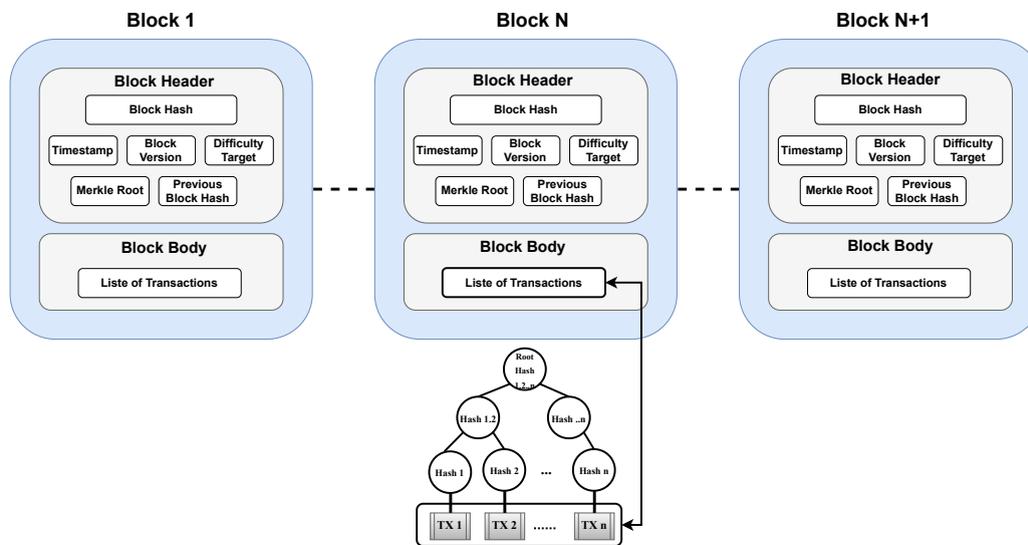


FIGURE 2.6: Blockchain data layer: Components and Structure

1. **Transactions:** Transactions is the transfer of data or assets between two or more network participants to their validation and grouping into blocks (see Figure 2.7) and each transaction contains structured data and multiple attributes includes the following elements [142, 180]:

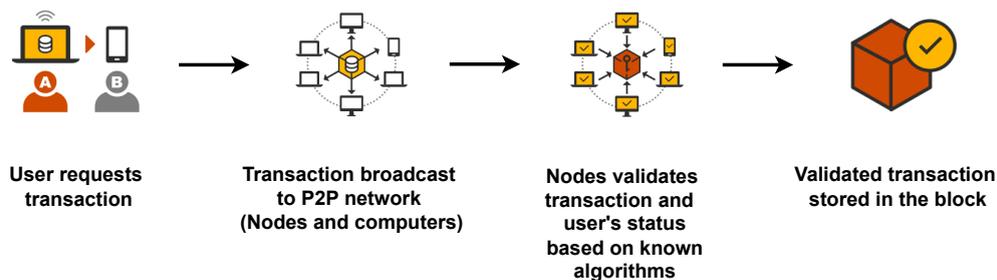


FIGURE 2.7: Transaction processing workflow in blockchain

- Transaction ID: A hash of the transaction data.
- Sender Address (Input): The public key or address of the node initiating the transaction.
- Receiver Address (Output): The destination address where the asset or data is sent.
- Input Data: References to previous transactions that are being used as inputs.
- Output Data: Details of how much value is transferred.
- Amount/Value: The quantity of digital amount or information being transferred.
- Timestamp: The exact time the transaction was created.

- **Digital Signature:** A cryptographic signature generated by the sender to ensure authenticity and prevent tampering.
 - **Smart Contract Code (if applicable):** Logic that defines additional conditions for execution.
 - **Nonce:** A counter used to ensure that transactions from the same address are processed in order (especially in Ethereum).
2. **Blocks:** Blocks are created as users participate in the blockchain network by submitting and creating transactions through various software interfaces such as desktop applications, mobile apps, digital wallets, or web services [466]. A block in a blockchain consists of two main components, each containing specific data and attributes essential for the integrity and operation of the network: the Block Header and the Block Body [197].
- **Block Header:** The block header contains metadata that ensures the security, traceability, and linkages within the blockchain. It includes:
 - **Version:** Indicates the version of the blockchain being used.
 - **Timestamp:** Records the exact time the block was created.
 - **Previous Hash:** A reference hash of the previous block, ensuring chain continuity.
 - **Merkle Root:** A hash representing all transactions within the block, generated through a Merkle Tree structure.
 - **Nonce:** A random number used in the proof-of-work process during mining.
 - **Difficulty Target:** Defines the mining difficulty level for the block.
 - **Block Height:** Specifies the block's position in the blockchain.
 - **Hash of the Current Block:** The cryptographic hash of the entire header, used to validate block integrity.
 - **Block Body:** The block body contains the actual transaction data and includes:
 - **Transaction Counter:** Specifies the number of transactions included in the block.
 - **List of Transactions:** A collection of validated transactions.
3. **Merkle Tree:** A Merkle Tree is a binary tree of hashes that enables efficient and secure verification of individual transactions without the need to process the entire block [238]. The structure starts from leaf nodes, which represent the hashes of individual transactions and then are paired and hashed together recursively until a single hash remains at the top this is known as the Merkle Root, which is stored in the block header [213]. The Merkle Tree enhances blockchain security and integrity through the use of cryptographic techniques, particularly hashing algorithms such as SHA-256 [341] and Keccak [59] that generate a fixed-size output (a digital fingerprint) from any input data, ensuring that even a small change in a transaction will produce a completely different hash. Another variant of the Merkle tree is the Merkle Patricia Tree (MPT), implemented in the Ethereum blockchain to overcome the limitations of Bitcoin-style light clients by supporting a dynamic state and combining three separate Merkle trees for transactions, receipts, and states which ensures cryptographic verification while preventing Denial-of-Service (DoS) attacks [94]. These two structures Merkle Trees in Bitcoin and Merkle Patricia Trees in Ethereum eliminate the tampering of transaction data and provide both security and immutability by enabling rapid and reliable verification of large volumes of transactions [212].
4. **Ledger:** The ledger in blockchain technology records all blocks of the network in a synchronized and immutable manner of data transactions, ensuring that every participant has access to the same data and eliminates the need for a central authority [53]. Modern

implementations, such as Hyperledger Fabric, introduce more flexible ledger architectures where the ledger is divided into a blockchain (immutable chain of blocks) and a world state (current state of the data), enabling high-performance querying and more efficient smart contract execution. In summary, the blockchain ledger serves as the single source of truth for all transactions in the system. It ensures data availability, historical traceability, and non-repudiation, which are critical in domains like finance, healthcare, and the food supply chain especially when trust and accuracy are non-negotiable [292].

Network layer

Nodes are individual devices such as computers that participate in the blockchain network by maintaining a copy of the ledger, validating transactions, or creating new blocks [209]. Depending on their responsibilities and level of participation, nodes are categorized into several types: Full Nodes, Light Nodes, or Mining/Validator Nodes [426, 446].

1. **Full Nodes:** Full nodes store a complete copy of the entire blockchain ledger from the genesis block to the most recent. They independently verify and validate every transaction and block according to the network rules [113].
2. **Light Nodes:** Light nodes do not store the full blockchain ledger and contain only the block headers and request specific data when needed using technique like Simplified Payment Verification (SPV) [476].
3. **Mining/Validator Nodes:** These nodes are responsible for proposing and adding new blocks to the blockchain [20]. For example, in Bitcoin mining nodes compete to solve cryptographic puzzles to validate blocks, and in Ethereum these nodes are selected to propose and attest blocks based on their staked assets.

Communication between these nodes occurs over a peer-to-peer (P2P) network, based on secure communication protocols such as gRPC, TLS, or custom P2P to exchange various types of messages, including block propagation, transaction dissemination, status updates, and consensus-related information [470]. The P2P communication layer in blockchain technology is essential for achieving decentralization, maintaining consensus, and ensuring data integrity across all participants in the blockchain network [396].

Consensus Layer

The consensus mechanism is a fundamental component of blockchain technology, its role is to ensure agreement on the validity of transactions and the current state of the ledger among distributed nodes [482]. Various consensus algorithms have been developed, and are generally classified into three main categories each characterized by distinct operational principles and trade-offs: Proof-based, Voting-based, and Hybrid-based mechanisms (see Figure 2.8). Among them, the most important and widely adopted algorithms are Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), Practical Byzantine Fault Tolerance (PBFT), and Proof of Authority (PoA). These key algorithms, along with a detailed comparison, are illustrated below.

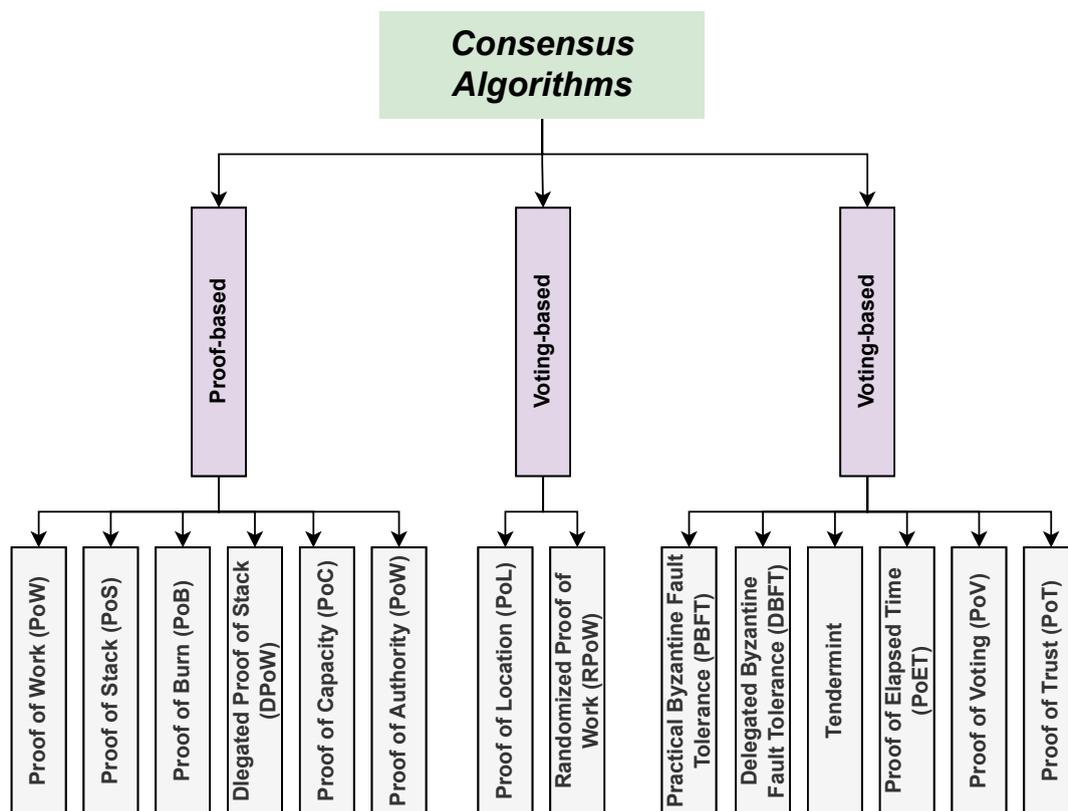


FIGURE 2.8: Classification of consensus algorithms [479]

1. **Proof of Work (PoW):** Used in Bitcoin, PoW requires participants (miners) to solve complex mathematical puzzles where the first miner that solve the puzzle have the right to add a new block to the chain and is rewarded with cryptocurrency [371]. While PoW offers high security and strong resistance to tampering, it suffers from high energy consumption and limited scalability due to its slow transaction throughput [141].
2. **Proof of Stake (PoS):** Introduced to address the energy inefficiencies of PoW, and is applied in platforms like Ethereum 2.0. In this model, validators are selected based on the amount of cryptocurrency they stake in the network and is chosen to propose or validate new blocks, eliminating the need for energy-intensive computations [186].
3. **Delegated Proof of Stake (DpoS):** In the DPoS algorithm, token holders vote to select a limited number of trusted delegates authorized to validate blocks on behalf of the community. This model improves efficiency and transaction speed while maintaining a degree of decentralization [166].
4. **Practical Byzantine Fault Tolerance (PBFT):** PBFT is designed for low latency and finality but is less scalable in large, open networks. It relies on multiple rounds of voting to reach agreement, ensuring that transactions are validated even in the presence of some compromised nodes [374].
5. **Proof of Authority (PoA):** In this model, nodes must prove and maintain their identities within the blockchain network, and the authority to publish new blocks is tied to the node's reputation where the higher a node's reputation have the chance being selected to validate and append blocks. This consensus mechanism is typically used in permissioned blockchain

networks where a high level of trust and identity verification is required among participants [450].

The variety of consensus mechanisms play a critical role in maintaining the security of the blockchain ecosystem and the choice of a specific consensus protocol significantly impacts the system's performance, scalability, and energy efficiency [445]. While Proof of Work (PoW) is chosen for its strong security, Proof of Stake (PoS) and Delegated Proof of Stake (DPoS) provide more scalable and energy-efficient alternatives, making the choice of consensus mechanism a critical design consideration in any blockchain-based system (see Table 2.3) [425].

Comparison Criteria	PoW	PoS	DPoS	PBFT	PoA
Energy Efficiency	Lowest (High consumption)	High	Highest	Highest	High
Transaction Speed	Slow (min/block)	Medium (sec/block)	Fast (sec/block)	Fastest (instant)	Fast (sec/block)
Decentralization	Full	High	Partial	Low (Permissioned)	Low (Identities)
Security Model	Hash power	Staked value	Elected delegates	Node votes	Approved validators
Governance	Miner competition	Staker voting	Delegate voting	Pre-selected nodes	Central authority
Use Case	Permissionless chains	Public blockchains	High-throughput DApps	Enterprise networks	Private chains
Examples	Bitcoin	Ethereum 2.0	EOS	Hyperledger	PoA Network

TABLE 2.3: Comparative analysis of consensus algorithms

Smart Contracts Layer

The concept of smart contracts was introduced in 1994 by Nick Szabo, who defined them as:

"A computerized transaction protocol that executes the terms of a contract. The general objectives of smart contract design are to satisfy common contractual conditions (such as payment terms, liens, confidentiality, and even enforcement), minimize exceptions both malicious and accidental, and minimize the need for trusted intermediaries. Related economic goals include lowering fraud loss, arbitration and enforcement costs, and other transaction costs"

— Szabo [383]

Given their many benefits, smart contracts have been incorporated into blockchain technology and are implemented as sets of code with multiple language such as solidity [90], VYPER [391], Rust [390], GO [83] and data that are published via cryptographically signed transactions on blockchain networks such as Ethereum (smart contracts) or Hyperledger Fabric (chaincode) [24]. The smart contract workflow is based on a series of coordinated steps executed within the decentralized blockchain network, as illustrated in Figure 2.9.

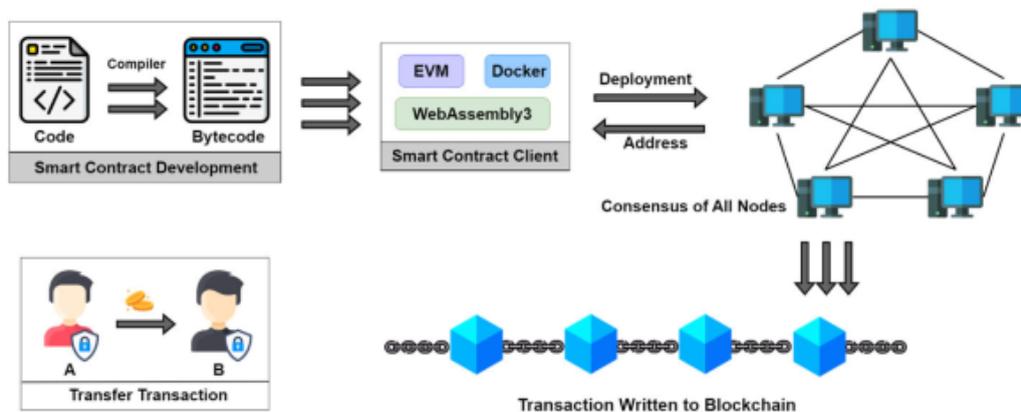


FIGURE 2.9: Smart contract workflow [97]

1. A user or an external application submits a transaction request to interact with a smart contract and then is broadcast to the network and received by the validating nodes.
2. The smart contract code, already deployed on the blockchain, is triggered and executed by these nodes based on the input parameters and the logic defined within the contract.
3. If the predefined conditions are met, the contract executes the corresponding operations, such as transferring assets or updating the ledger.
4. The result of this execution is recorded in a new block, ensuring immutability and transparency.

These self-executing programs are stored on the blockchain and executed by network nodes when predefined conditions are met, without the need for human intervention which improve process automation, reduce transaction costs, and eliminate the need for intermediaries (see Table 2.4). These principles are particularly valuable in areas such as supply chain management, insurance, and financial services, where transparent, secure, and automated implementation of agreements is essential [278].

Feature	Normal Transactions	Smart Contract Transactions
Purpose	Transfer of tokens/assets	Execute predefined programmable logic
Initiation	Manually by users	Manually or triggered automatically
Complexity	Simple	Complex (conditions, loops, etc.)
Validation	Signature, balance check	Includes code execution validation
State Change	Ledger balance update	Contract state and blockchain update
Example	Alice sends 2 ETH to Bob	If Bob submits proof, then release 2 ETH

TABLE 2.4: Comparison of transaction creation methods: Normal vs. Smart Contract-based

2.2.5 Applications

Due to the features discussed previously, blockchain has become a powerful tool in complex systems, addressing long-standing challenges such as fraud, data fragmentation, lack of transparency, and manual inefficiencies. As blockchain technology continues to evolve, its impact has extended far beyond cryptocurrency, finding valuable applications in various industries [314]. This section explores key domains where blockchain is actively integrated, including finance, supply chain and logistics, energy, healthcare, and education. Figure 2.10 illustrates the applications of blockchain technology in different sectors.

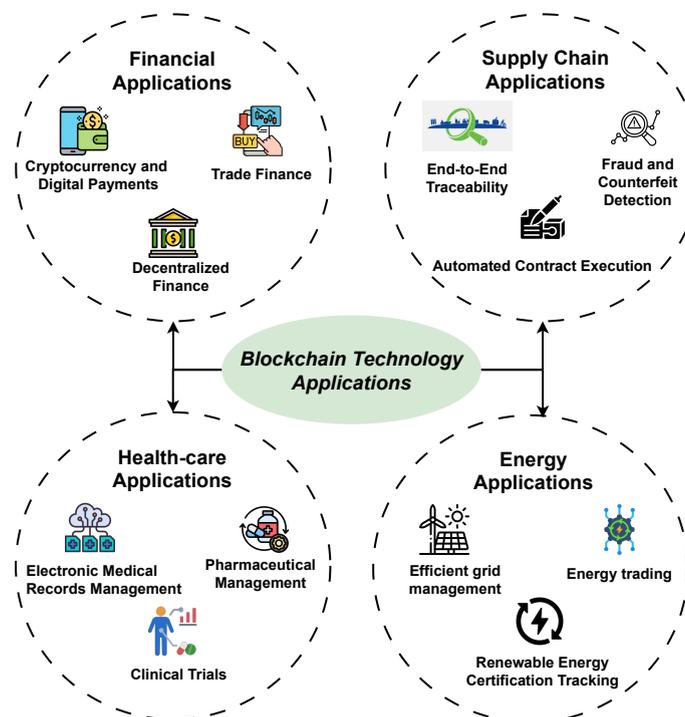


FIGURE 2.10: Blockchain technology applications

Financial Applications

Blockchain technology is widely used in cryptocurrency applications due to the high sensitivity and need for robust security and transparency. It facilitates secure, decentralized transactions between users who transfer significant amounts of digital currency. While the initial success of blockchain was closely tied to cryptocurrencies like Bitcoin, the technology has since expanded to revolutionize a wide range of financial services such as decentralized finance (DeFi), automates agreements through smart contracts, reduces operational time and costs for financial institutions, and supports tokenization of assets [459].

- **Cryptocurrency and Digital Payments:** Blockchain technology is applied to improve digital payments by offering decentralized alternatives to traditional currencies, such as Bitcoin, Ethereum, and Litecoin [148]. These systems enable peer-to-peer transactions without the need for intermediaries like banks, ensuring transparency, security, and global accessibility.

- **Trade Finance:** Trade finance traditionally suffers from inefficiencies, lack of transparency, and trust issues due to multiple intermediaries in countries. Blockchain simplify this process by providing a shared, immutable ledger where all parties including buyers, sellers, banks, and insurers can access the same information in real time which reduces delays, manual verification, and the risk of document fraud [51]. For example, [176] introduces a blockchain-based smart contract system that enhances trust and security in international trade by automating verification and execution of agreements. Blockchain also addresses information asymmetry, as noted in [440], by enabling synchronized data sharing, which enhances operational clarity and reduces disputes among trade participants.
- **Decentralized Finance (DeFi):** Decentralized Finance (DeFi) leverages blockchain to provide financial services without central intermediaries especially with the use of smart contracts. These services operate on protocols like Ethereum and are governed by transparent code rather than institutions, empowering users with greater control over their assets. The success of initiatives such as Santander’s blockchain-based payment networks and the integration of blockchain into national taxation systems highlights its utility in creating a more transparent, automated, and inclusive financial ecosystem [188, 340].

Supply chain and logistics Applications

The supply chain encompasses the entire process of producing and delivering goods, services, or data, from sourcing raw materials to delivering the final product [372]. Existing supply chain systems face significant challenges, such as data tampering, low query efficiency, auditing difficulties, and high management and verification costs [125, 252]. Addressing these challenges based on blockchain technology is critical to improving the efficiency and reliability of supply chain systems.

- **End-to-End Traceability:** End-to-end traceability in supply chain and logistics based on blockchain allows stakeholders to track and verify the movement, condition, and provenance of goods at every stage [193]. By leveraging blockchain’s immutable and time-stamped records, organizations can ensure that each transaction or event is verifiable, transparent, and auditable [357]. For instance, the work in [438] introduces a dual storage model using Hyperledger blockchain, which significantly enhances the performance and integrity of traceability queries. Similarly, [259] presents ProductChain, a permissioned blockchain architecture that balances confidentiality with public provenance, ensuring efficient data retrieval across multiple shards. In [70], a blockchain system specific for dairy supply chain improves compliance, boosts consumer trust, and strengthens safety by providing clear trace paths for all product movements. Additionally, the system in [161] for Aircraft Spare Parts Management ensures traceability in aviation logistics, enhancing information visibility and data accuracy within critical operational environments.
- **Fraud and Counterfeit Detection:** Blockchain considered as a powerful tools for preventing fraud and counterfeit activity in supply chains by enabling transparent recording of every information and helps authenticate the origin and history of goods, thereby reducing the risk of unauthorized alterations and fake products [34]. In [272], blockchain technology is applied to the agricultural supply chain, establishing a decentralized database that not only stores data in real time but also enables secure querying and validation of product quality. This framework helps detect tampering and prevent falsification of product attributes. Similarly, [13] applies blockchain in the textile and clothing industry,

where information asymmetry and lack of visibility are critical concerns thereby increasing transparency and reducing fraud.

- **Automated Contract Execution:** Smart contracts is another transformative blockchain application in supply chains play as a self-executing programs stored on the blockchain and eliminating the need for manual intervention or intermediaries. This automation improves efficiency, reduces transaction delays, and enforces contractual agreements with precision [105]. For example, the blockchain-based system in [263] utilizes self-executing smart contracts to ensure secure, tamper-proof transactions between untrusted parties.

Healthcare management Applications

In healthcare, blockchain technology enhances data security, patient privacy, and medical record interoperability [289]. Electronic Medical sensors capture information such as prescribed medications, injections, surgeries, and data from wearable e-health devices powered by IoT sensors, which continuously monitor and represent the state of a patient [17]. However, applications in this domain face various challenges and issues related to data integrity and access control for real-time decision making that require the integration of blockchain technology in various fields of healthcare management [39].

- **Electronic Medical Records Management:** Blockchain technology offers an effective solution for managing electronic medical records, ensuring tamper-proof storage and enhanced privacy. Patient records stored on the blockchain are encrypted and accessible only to authorized parties, allowing control over who can access their data [172]. This decentralized access model reduces the risk of data breaches and enhances interoperability between hospitals, clinics, and health service providers. Several studies [195, 484, 487] have implemented blockchain-based systems for medical data management, demonstrating scalability, low storage overhead, and strong resistance to attacks through encryption mechanisms. The work in [460] uses an IPFS-based architecture to decentralize EMR storage while maintaining data confidentiality. In addition, [77] use blockchain with K-anonymity and searchable encryption to protect patient privacy, while smart contracts ensure that only authorized users can access the records.
- **Pharmaceutical Supply Chain:** By using blockchain technology in this field, the authenticity and safety of pharmaceutical products can be ensured through end-to-end traceability from manufacturers to patients. Each information such as manufacturing dates, batch numbers, and handling conditions is immutably recorded on the blockchain, allowing regulators and supply chain stakeholders to verify product authenticity at any stage, and respond promptly to public health risks [3]. The work in [352] applies blockchain for drug traceability, thus improving transparency and accountability in pharmaceutical logistics. Another study [363] explores blockchain applications for tracking pharmaceuticals from production to distribution, ensuring product authenticity and effective expiry management. It also highlights the importance of integrating blockchain with IoT and AI to enhance transparency across the pharmaceutical supply chain.
- **Clinical Trials:** Blockchain enhances the integrity and transparency of clinical trials by providing an immutable record of all data, including patient consent forms, research protocols, and results. It allows researchers and regulators to access synchronized, time-stamped data, reducing discrepancies and improving auditability. Moreover, blockchain can streamline participant recruitment and consent management, ensuring that patients

rights are preserved and ethical guidelines are followed. For example, in [395, 471] demonstrates how blockchain features such as encryption and consensus-driven validation enhance data integrity and security in clinical trials. These capabilities are essential for establishing a trustworthy, transparent, and verifiable ecosystem in biomedical research and drug development.

Energy sector Applications

Traditional energy systems often suffer from several problems, such as poor efficiency, centralized oversight, and lack of transparency [422]. To this end researchers have leveraged blockchain technology to address these limitations by enabling peer-to-peer (P2P) energy trading, improving grid stability through real-time data sharing, and ensuring trust in environmental compliance processes [423]. In the following subsections, we present how blockchain technology supports energy systems through several mechanisms, such as: decentralized energy trading, efficient grid management, and renewable energy certification tracking paving the way for a more efficient, sustainable energy system.

- **Decentralized Energy trading:** Blockchain-enabled distributed trading platforms are revolutionizing the energy sector which facilitates decentralized peer-to-peer (P2P) energy trading systems and allowing consumers who generate renewable energy such as solar or wind power to sell the electricity directly to others [31]. This approach eliminates the need for centralized utility intermediaries and significantly reduces transaction costs. Furthermore, smart contracts simplify this process by automating energy trading transactions, ensuring transparency, security, and efficiency.
- **Efficient Grid Management:** For grid infrastructure management, blockchain helps utilities and grid operators to efficiently manage energy data from storage units by recording usage, operational status, and maintenance logs on a unified, tamper-proof ledger [191]. It also facilitates automated demand response and grid balancing by enabling secure, real-time communication among distributed energy resources (DERs) [133]. This capability is particularly essential as smart grids and IoT devices generate vast amounts of data that demand integrity, synchronization, and rapid decision-making [326].
- **Renewable Energy Certification Tracking:** This techniques used to verify that a certain amount of energy was generated from renewable sources or that a corresponding amount of emissions has been offset [488]. These mechanisms are essential in the energy sector but face challenges related to transparency, fraud, and double counting [65]. Blockchain technology addresses these issues by ensuring transparent and tamper-proof issuance, tracking, and trading of RECs and carbon credits. For example, with blockchain-based systems, regulators and buyers can verify the origin, ownership, and validity of each certificate in real time [241]. In addition, smart contracts can automatically enforce regulatory rules and build trust between companies, governments, and individuals who participate in sustainability and carbon offset programs [154].

2.3 Blockchain Technology in Food Supply Chain

With the advancement of blockchain technology to its fourth generation (Blockchain 4.0) with the integration into various industries, the supply chain sector characterized by its distributed

structure, multiple stakeholders, and data vulnerabilities stands out as a particularly suitable domain for blockchain implementation [43, 71, 76, 320, 417]. In particular, the food supply chain requires high levels of traceability and safety, making it an ideal sector for blockchain-based solutions [375]. This section explores the integration of blockchain technology into the food supply chain process, examining its architecture, core benefits in enhancing food safety, its role in improving food safety techniques, real-world use cases, and the key challenges associated with its adoption.

2.3.1 Integration

Existing food safety systems often struggle to meet current demands and fail to adequately manage the complexity of food supply chains, primarily due to the involvement of multiple, independent operating actors with diverse requirements and data management standards [328, 381]. Each stakeholder in the food supply chain has unique needs that current systems often fail to fulfill:

- **Farmers and Producers:** Require real-time data on soil conditions, weather forecasts, and sustainable farming practices to improve agricultural production [282].
- **Manufacturers and Processors:** Rely on traceability data to verify the sources of raw material, monitor processing conditions and ensure compliance with food safety regulations [349].
- **Logistics:** Need secure tracking mechanisms to monitor shipment routes, temperature conditions, and delivery confirmations [40].
- **Retailers:** Depend on transparent records to verify product authenticity and compliance with safety standards.
- **Consumers:** Expect detailed information on product origin, certifications, and quality assurance to make informed purchasing decisions.

To address these challenges and requirements, blockchain technology with its decentralized, immutable, and transparent architecture, has gained significant interest in the food supply chain by incorporating distributed ledger technology into various stages of the supply chain to record every data information in a tamper-proof and verifiable manner. This includes the capture of critical data such as food origin, processing methods, storage conditions, transportation events, and certifications and then applied there food safety mechanisms based on this technology. Figure 2.11 demonstrates the integration of blockchain technology in the food supply chain.

2.3.2 Architecture of Blockchain-based FSC

In this section, we present the architecture of the food supply chain process based on blockchain technology and presents the combination of their architectures to enhance data management and ensure the food safety features. The integration of blockchain in the food supply chain follows similar concepts to cryptocurrency networks due to the shared architectural principles, enabling efficient data extraction, data management and data presentation and query [343]. The architecture model of the food supply chain based on blockchain technology is depicted in Figure 2.12.

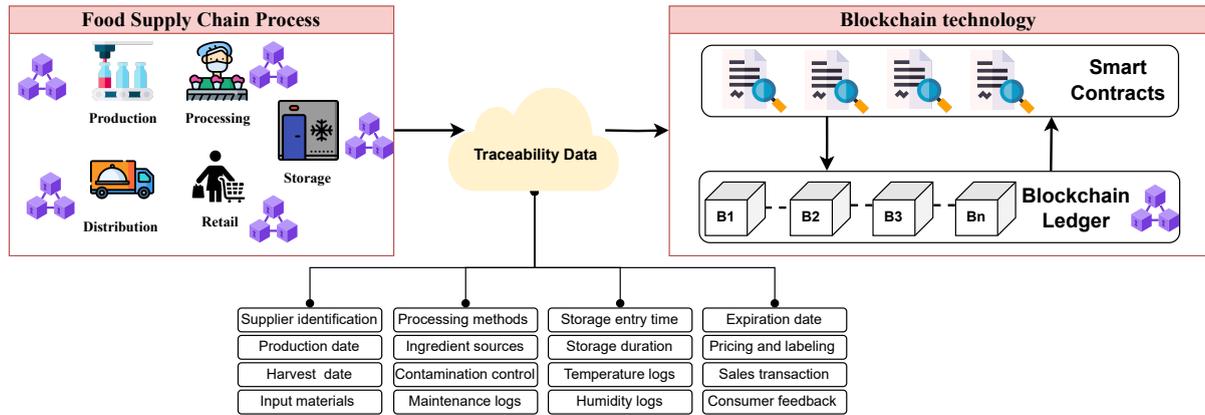


FIGURE 2.11: Blockchain integration in food supply chain

Physical Layer

The physical layer in the blockchain-based food supply chain is represented by the distributed stages of the supply chain, involving various entities and actors such as farms, production facilities, processing centers, warehouses, transportation vehicles, and retail which act as nodes and participants in the blockchain network. This layer, integrated with IoT devices and ICT technologies such as RFID tags, temperature sensors, GPS trackers, and barcodes facilitates the collection and traceability of real-time data related to environmental conditions at each stage in the chain. It also enables transactions between nodes and ensures that the collected data is recorded and stored securely on the system [42].

Network Layer

The network layer represents the peer-to-peer communication without intermediaries between distributed nodes in the blockchain network that represents the FSC distributed stages [380]. Based on blockchain technology this facilitates real-time data exchange, ensuring that critical information such as product origin, processing, storage conditions, and transportation is securely and transparently transmitted across the blockchain network [227].

Consensus Layer

The consensus layer in the food supply chain based on blockchain technology defined by a specific algorithm responsible for validating data transactions and ensuring user agreement on a set of transactions, this guarantees that all supply chain participants rely on a unified and tamper-proof ledger, reducing the risk of fraudulent activities and manipulation of food data [370, 384]. However, this layer suffers from several attacks that can compromise data integrity by allowing entities to alter transaction records and falsify traceability data. Common threats include bribe attacks, long-range attacks, and Sybil attacks, which highlight the need for strong security measures to ensure data authenticity and reliability [312].

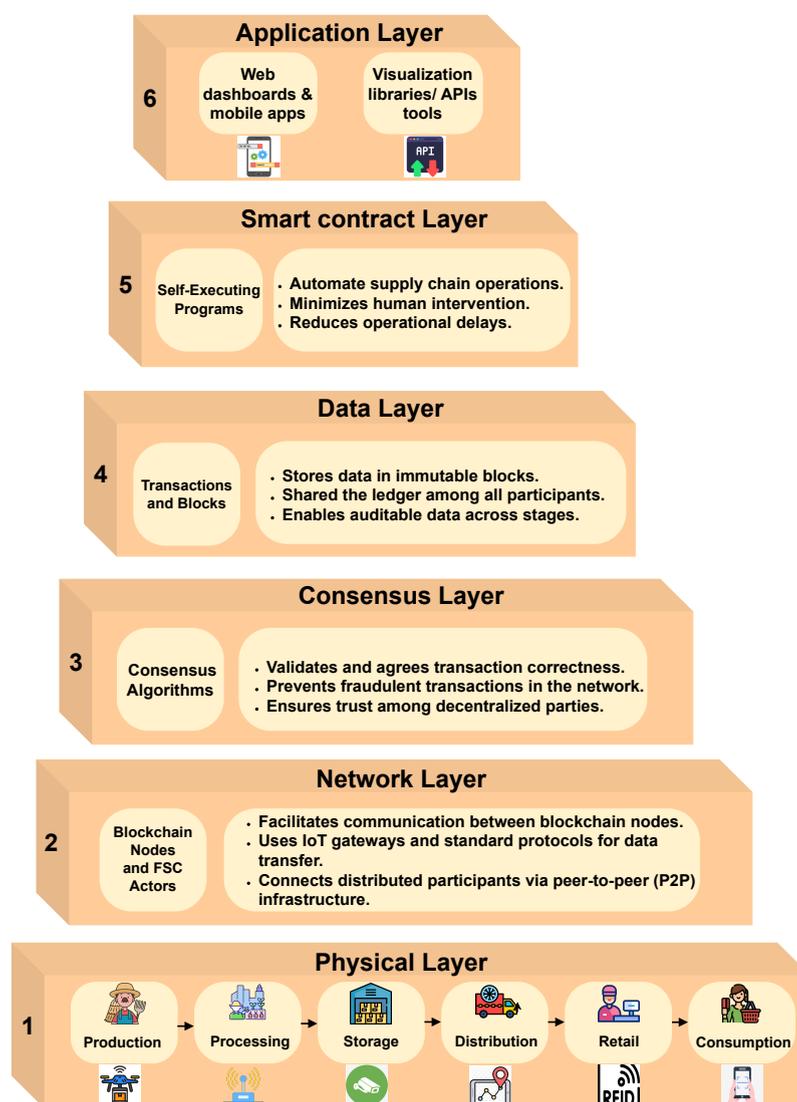


FIGURE 2.12: Blockchain-based food supply chain architecture

Data Layer

The data layer represents the storage and data management within the blockchain network, ensuring efficient, transparent, and secure food supply chain operations [469]. Each block contains essential attributes related to food products, such as production details (e.g., farm location, harvest date, and farming practices), quality certifications (e.g., organic, halal, or gluten-free certifications), temperature logs (critical for perishable goods like seafood, dairy, and meat), and delivery timestamps (to track product movement across the supply chain) [6]. Transaction data in this layer is stored sequentially and structured using a Merkle tree, with advanced cryptographic techniques ensuring protection against unauthorized modifications, thereby enhancing security and reliability in the food industry. Additionally, the blockchain ledger and its updates is distributed across all the participants of the network [28].

Smart Contract Layer

The smart contract layer in the food supply chain architecture contains programmable logic that defines and enforces various operational rules, such as sending shipments when delivery conditions are met, triggering alerts when temperature thresholds are exceeded, or verifying the validity of credentials. This enables real-time decision-making, reduces human error, and ensures operational consistency [91]. Smart contracts, leveraged by blockchain technology in the food supply chain, support a variety of use cases:

- **Quality Assurance and Safety Control:** Smart contracts can enforce rules that block expired, spoiled, or improperly handled goods from reaching retailers, thereby enhancing food safety and consumer trust.
- **Data Query and Access Control:** They manage access permissions by defining who can query specific data, ensuring privacy and controlled data access in consortium blockchain environments.
- **Inventory and Logistics Management:** Smart contracts automate tasks such as restocking, shipment scheduling, and warehouse updates based on predefined conditions or inventory levels.
- **Traceability and Transparency:** They enable stakeholders to query a product's information, handling conditions, and its journey through the supply chain, fostering transparency and accountability.

Application Layer

The application layer is the topmost layer in blockchain architecture, designed for food supply chain users, including producers, suppliers, retailers, regulatory bodies, and consumers, to interact with the blockchain system [394]. It provides access to key functionalities such as food traceability, product authentication, transaction verification, and supply chain analytics. This layer incorporates a wide range of tools and interfaces, including user dashboards, mobile applications, and Blockchain APIs that enable users to securely retrieve and input food-related data [55]. Notable examples of blockchain APIs used in this context include [302]:

- **Hyperledger Fabric SDKs (Node.js, Java, Go):** Allow applications to interact with smart contracts (chaincode), submit transactions, and query the ledger.
- **Ethereum Web3.js / Web3.py:** Enable dApps to communicate with Ethereum-based networks to query data and execute transactions.
- **IBM Blockchain Platform APIs:** Provide enterprise-grade APIs for accessing traceability features in food supply chain solutions.
- **VeChain ToolChain™ APIs:** Offer food safety and tracking services tailored to agri-food industries, enabling product lifecycle management and anti-counterfeiting verification.

Due to the extensive communication and interconnectivity required at this layer, the application layer is highly exposed to security threats such as Distributed Denial of Service (DDoS) attacks and unauthorized access, which can compromise sensitive data and disrupt services [346]. To

ensure robust and secure interaction, this layer often implements authentication mechanisms and encrypted data channels to safeguarding the integrity and availability of food supply chain services.

2.3.3 Benefits

The integration of blockchain technology in the food supply chain offers numerous advantages over traditional systems, positioning it as a superior solution in many respects. Native features of blockchain such as traceability, security, and immutability bring significant benefits to food supply chain operations which enhance transparency, protect data integrity, and enabling reliable tracking of food products across all stages of the supply chain, thereby improving food safety and quality assurance. The most important benefits enabled by blockchain in the context of the food supply chain are illustrated in Figure 2.13 and summarized below.

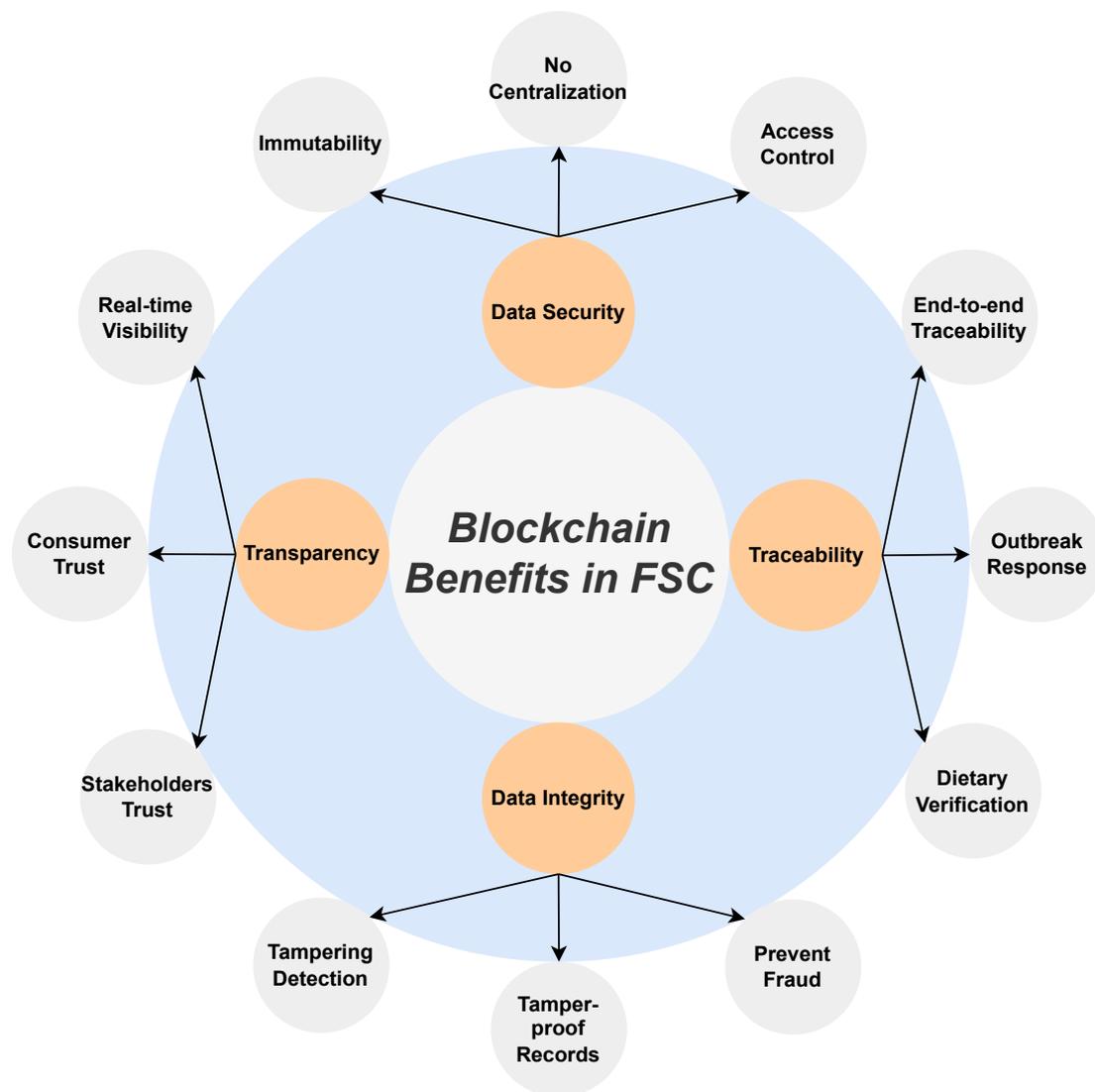


FIGURE 2.13: Blockchain benefits in food supply chain

Transparency

Transparency is one of the most important requirements in the modern food supply chain which are vulnerable to manipulation by anyone and the integration of blockchain technology achieved this benefit via a shared ledger that is accessible to all participants and enables users and actors to view all data changes and updates in real time which builds trust among stakeholders, including consumers, who can verify the authenticity and safety of food products [38, 273]. For example, Nestlé uses blockchain to provide transparency for its Zoégas coffee brand, allowing consumers to trace the journey of their coffee beans and ensuring transparency in the processing stages which encourages accountability and ethical practices across the supply chain [323].

Traceability

Traceability is another key feature offered by blockchain technology in the food supply chain process, ensuring that data transactions stored in the distributed ledger are tracked and accessible to authorized participants. This capability enhances food safety by allowing stakeholders to quickly identify the source of contamination during a foodborne illness outbreak, minimizing risks and enabling timely recalls [162]. Additionally, it encourages all parties to remain accountable for their actions and data decisions, as blockchain-based traceability records every movement, transformation, or transaction, creating a transparent and auditable trail [69]. For example, IBM Food Trust uses blockchain for traceability of products like mangoes and pork, enabling stakeholders to trace their origin in just a few seconds [185]. This feature significantly impacts food safety by allowing stakeholders to quickly identify the source of contamination in the event of a foodborne illness outbreak, minimizing risks and ensuring timely recalls.

Data Security and Integrity

Data security and integrity in the blockchain-based food supply chain are ensured by eliminating centralized control and third-party intermediaries in data exchanges between FSC actors [404]. For example, in the seafood industry, multiple suppliers collect and exchange critical data, including certifications, inspection reports, and temperature logs during transportation. Blockchain technology secures this data by encrypting and distributing them across a decentralized network using cryptographic techniques and digital signatures, ensuring its integrity which only authorized parties can access the data using cryptographic keys [168, 324].

2.3.4 Applications

The application of blockchain technology in the food supply chain has proven its potential to solve food safety challenges related to data transparency, traceability, and integrity. This section highlights key use cases where blockchain technology is delivering tangible improvements in food safety across different stages of the supply chain. Figure 2.14 illustrates the different blockchain applications within the food supply chain.

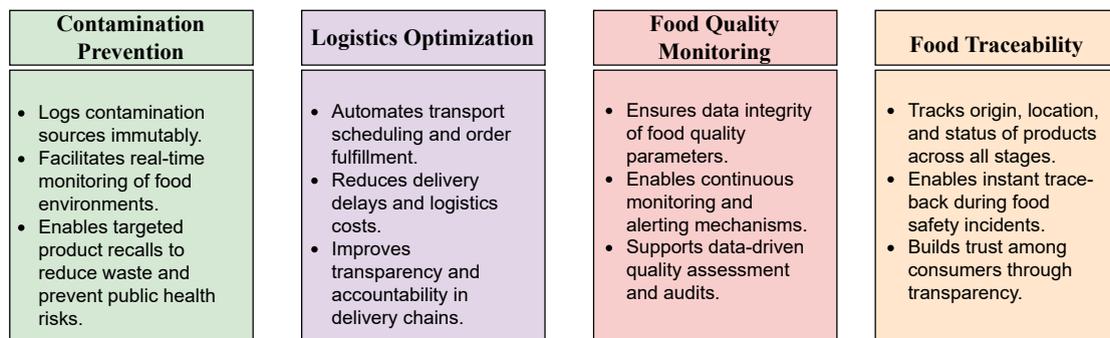


FIGURE 2.14: Blockchain applications in food supply chain

Contamination Prevention

Blockchain technology enables the food industry to build a more resilient and secure system to combat contamination, ultimately improving food quality and protecting public health. By leveraging blockchain's transparency and traceability, stakeholders in the food supply chain can detect and track affected products, respond to environmental conditions contributing to contamination in real time, facilitate targeted recalls, and minimize health hazards [170].

To enhance contamination prevention, blockchain is often integrated with IoT technologies such as Radio Frequency Identification (RFID), Near Field Communication (NFC), and Wireless Sensor Networks (WSNs). These technologies support real-time identification of contamination sources and when combined with blockchain, they allow for continuous monitoring, automated data collection, and decentralized tamper-proof storage, all of which contribute significantly to faster and more accurate contamination detection and response [240].

- **Real-Time Risk Monitoring:** Integrating blockchain with IoT sensors in food supply chain enables real-time monitoring of contamination risks across every stage of the food supply chain. For instance, the work in [86] proposed a safety system for tracking nuclear contamination in seafood using WSN and RFID technologies combined with blockchain. Another system developed in [397], monitor contamination risks in real-time across production, processing, warehousing, and distribution stages highlighted how a real-time monitoring application based on blockchain technology enhances food safety in the food supply chain.
- **Efficient Recall Management:** Blockchain greatly improves recall management by enabling the quick and precise identification of contaminated product batches, ensuring that affected goods are quickly removed, thereby reducing both economic losses and consumer risks. For example, the study [311] examined how RFID, combined with blockchain, improves the accuracy and speed of identifying contamination sources, leading to more effective recall strategies. Similarly, in [248], the authors highlighted blockchain's role in enhancing traceability and recall effectiveness during contamination events. In [170] the system focused on how blockchain maintains tamper-proof sanitation records and reduces contamination risks at every supply chain stage. Furthermore, [481] focused on how blockchain maintains efficient recall by proposed techniques to locate contamination events with greater precision within a blockchain-enabled food supply chain.

Logistics Optimization

Blockchain technology is increasingly applied in logistics optimization due to its ability to ensure a seamless flow of goods and fix several challenges, including a lack of real-time visibility, inefficient inventory management, delays in transportation and vulnerability to fraud or miscommunication between stakeholders [307]. In addition, it must be integrated with advanced technologies such as robotics and automation, big data, IoT, and AI to process large volumes of data from various sources, enabling actionable insights that optimize forecasting, inventory control, and transportation management [137].

- **Transparent Shipment Tracking:** Blockchain enables the recording of every transaction, location update, and product status in a tamper-proof ledger, increasing trust among stakeholders and reducing delivery disputes. Several works propose blockchain-based solutions for enhancing real-time tracking and optimizing logistics. One such study, [366] uses Ethereum smart contracts and a Proof of Stake (PoS) mechanism to automate and secure shipment status updates and offers decentralized, real-time shipment visibility to reduce delays, fraud, and operational costs. Another work in [160], introduces a cloud-based portal integrating RFID, IoT, and blockchain technologies to connect transport companies and consolidation points, offering transparent and immutable transaction histories along with performance monitoring through key indicators. In [152], researchers propose a blockchain solution for real-time shipment monitoring using smart containers with IoT sensors to enforce shipment conditions such as temperature, humidity, and location and automated actions like payments.
- **Smart Contract Automation:** Smart contract automation is another technique that ensures logistics optimization by automatically enforcing logistics agreements such as payments upon delivery or dynamic rerouting in case of delays. In [392], smart contracts demonstrate secure and automated logistics operations and are used for ingredient tracking and verification which fosters trust among system parties. Another study, [467], introduces a decentralized food delivery platform that leverages blockchain and smart contracts to eliminate commissions, ensure authentic reviews, and enhance recommendation accuracy using a deep learning model.

Food Quality Monitoring

Blockchain enhances food quality monitoring in vulnerable regions where food logistics are more challenging by storing real-time data with secure timestamps and enabling accurate tracking with rapid responses to supply chain disruptions. Combining blockchain with IoT improves data collection across the food supply chain stages, facilitates traceability, and empowers stakeholders with timely information for intervention. Additionally, AI and big data analytics further another technologies can be integrated with blockchain to enhance monitoring by enabling smart decision-making based on historical and real-time trends [477].

- **Real-Time Data Monitoring:** IoT sensors monitor key environmental parameters like temperature and humidity in real time. These readings are recorded on the blockchain, allowing stakeholders to detect and respond to anomalies that could impact food quality. For instance in [129] the system focuses on real-time monitoring of environmental conditions using a portable data logger with wireless communication. Another study [19]

integrates blockchain technology for real-time monitoring of environmental conditions in the food supply chain. By combining IoT devices and distributed databases, it captures detailed carbon emissions data throughout various stages, ensuring transparency, privacy, and collaboration among participants.

- **Predictive Quality Analytics:** Artificial Intelligence combined with blockchain records can predict spoilage risks and food quality degradation, allowing proactive responses to maintain freshness and prevent losses. For example, the system in [202] uses AI and IoT technology for real-time food quality monitoring and demonstrates high accuracy in monitoring environmental conditions across the supply chain, achieving 95.2% accuracy under normal conditions and adaptability under hard conditions. Another study, [306], proposes an IBBA framework that combines IoT, blockchain, and AI for real-time environmental monitoring. This framework enables early contamination detection and supports informed decision-making, enhancing food safety and reducing risks associated with food production.

Food Traceability

Blockchain technology enhances food traceability by providing real-time access to immutable data about food products, allowing consumers and stakeholders to verify the origin, quality, and compliance of products across the supply chain [96]. Furthermore, the integration of blockchain technology with IoT devices improves communication between system components, enabling accurate tracking of food-related data. For example, RFID tags facilitate secure data collection and automated transfer across all supply chain stages, boosting transparency and food safety. QR codes are also a key ICT technology, widely used to provide an accessible interface for consumers to verify product authenticity [277, 397].

- **Farm-to-Fork Product Tracing:** This application enables the full tracking of the journey of food items from their origin to the final consumer, allowing the verification of traceability information such as origin, journey, and compliance. The study in [131] tackles transparency issues in agri-food service supply chains by using IoT sensors and blockchain for real-time tracking and smart contracts to automate compliance and data sharing. It offers a practical framework for blockchain adoption to enhance traceability, fraud prevention, and regulatory compliance. Another work in [222] highlights inefficiencies in manual agricultural product tracking and proposes a blockchain-IoT solution for automated and decentralized data capture. The system ensures data integrity and stakeholder accountability, providing a semi-automated method to improve traceability and reduce the risks of data tampering or loss throughout the agricultural supply chain. Furthermore, [368] addresses agricultural supply chain weaknesses in terms of traceability and improves real-time traceability at all supply chain stages.
- **Source Verification and Authenticity:** Blockchain ensures the verification of food origin, preventing fraud and mislabeling. For example, it can confirm whether 'organic', 'halal' or 'locally sourced' claims are authentic by tracing the product's exact source and certifying authorities. The study in [376] proposes a blockchain-based system to monitor, trace, and authenticate agricultural products, addressing food safety concerns. The results confirm the system efficiency in verifying product origins and enhancing traceability across the entire supply chain. Similarly [192] combines blockchain, IoT, and deep learning for source verification in food systems with a hybrid prediction model that processes real-time IoT data to detect anomalies and verify authenticity which enhances smart traceability and supports data-driven decision-making in supply chain management.

2.4 Challenges and Limitations

Although blockchain technology offers significant advantages to the food supply chain particularly in enhancing food safety it also faces several practical and technical limitations that can hinder its effective implementation (see Figure 2.15).

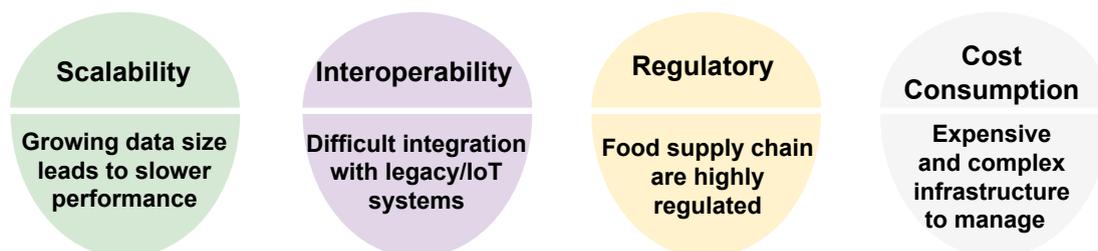


FIGURE 2.15: Challenges of blockchain technology in food supply chain

- **Data Scalability:** As the volume of data increases in the food supply chain, the size of the blockchain ledger increases, making the storage and processing of transaction data inefficient.
- **System Interoperability:** Integrating blockchain with legacy food tracking systems and IoT platforms can be complex due to inconsistent data formats and standards.
- **Regulatory:** Many industries such as food supply chain are highly regulated, and blockchain technology may not comply with existing regulations. This can make it difficult for companies in these industries to adopt blockchain, as some stakeholders may hesitate to share sensitive business data openly, creating a tension between openness and confidentiality.
- **Cost and Complexity of Implementation:** Deploying and maintaining a blockchain infrastructure (including smart contracts, consensus protocols, and peer nodes) requires significant technical expertise and investment.

In most blockchain architectures, the food supply chain process is represented by a large number of blocks, and traceability information is distributed across them. When a query is made to retrieve specific historical data (e.g., the origin of a contaminated product), the system often must perform a sequential scan across all blocks which becomes increasingly inefficient as the blockchain grows, resulting in delays in real-time decision-making. These challenges highlight the need for optimized data management techniques, particularly indexing solutions, to improve the efficiency of traceability queries and make blockchain a more scalable and practical tool for real-world food supply chain applications.

2.5 Conclusion

In this chapter, we improve the utilization of blockchain technology as a new solution to ensure food safety in the food supply chain through data traceability, transparency, and integrity. We examine the foundational principles of blockchain technology, architecture, and its integration into various industrial sectors, then focus to its adoption in the food supply chain, where

blockchain is increasingly used to ensure real-time visibility, reduce fraud, and support compliance with safety standards. There are still several limitations that hinder the full effectiveness of blockchain in this field, especially when it comes to data scalability and the inefficiency of tracing queries due to sequential access to data across the blockchain ledger. These limitations underscore the need for advanced solutions, such as indexing techniques, to improve query performance and make blockchain-based systems more practical for real-world food supply chain applications. This chapter sets the stage for the next chapter, where we explore indexing structures as a promising direction to overcome these challenges and build more efficient and intelligent traceability systems.

CHAPTER 3

BLOCKCHAIN QUERY MANAGEMENT AND INDEXING TECHNIQUE

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3.1 Introduction

The rise of traceability query techniques in the food supply chain has ensure the food safety at various stages. However, the large volume of data generated from these stages based on IoT techniques, combined with its complexity and distributed nature, makes traditional traceability systems inefficient. As a result, there is a critical need for optimized solutions to improve traceability queries particularly in large-scale food supply chain applications by enabling fast and efficient access to traceability information and services. In this chapter, after examining blockchain technology in food supply chain systems and identifying the limitations of traceability queries, we shift the focus to improve data retrieval through indexing techniques. We introduce the development of optimization techniques application in blockchain technology that aim to improve traceability queries using methods such as external databases and smart contracts. Additionally, we explore key areas within blockchain systems where indexing techniques can be effectively applied to support scalable and high-performance traceability operations. Finally, the chapter presents the fundamental concepts of different indexing structures and search mechanisms, along with an overview of its features.

3.2 Query Management Applications in Blockchain Systems

Traceability query management in blockchain systems has seen notable advancements in recent studies, introducing novel methods that address the limitations of traditional blockchain querying. These approaches focus on enhancing query speed, minimizing computational overhead, and ensuring data integrity and security [325, 338, 451]. In this section, we present a classification of query optimization applications in blockchain technology categorized into three main areas: approaches based on external databases, smart contracts, and indexing structures to offer a clearer understanding of the evolution and scope of these techniques (see Figure 3.1).

3.2.1 Based on External Databases

Query optimization based on external databases relies on various techniques, including middleware solutions [434], blockchain databases [52], and big data integration frameworks [204]. These external solutions overcome the limitations of native blockchain querying, such as sequential data access and limited query capabilities [315].

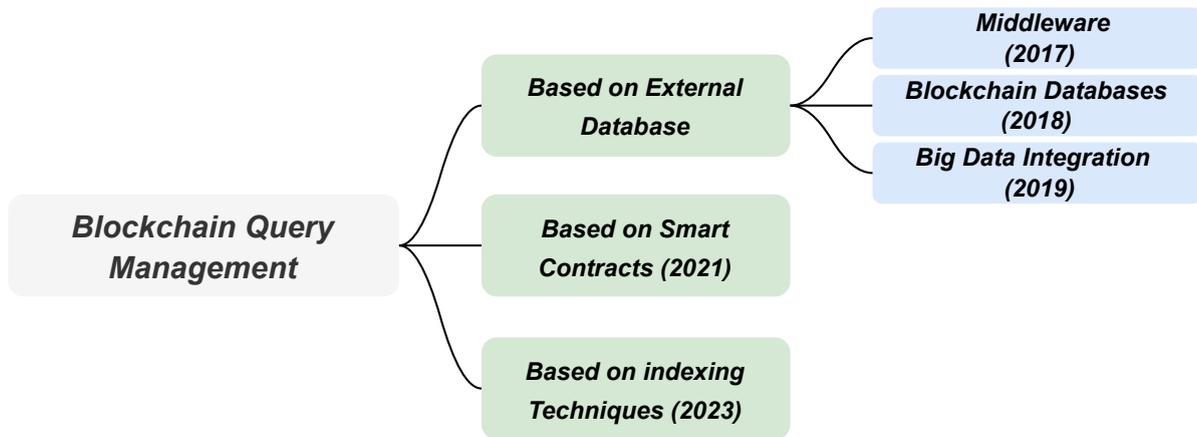


FIGURE 3.1: Blockchain query optimization approaches

Middleware

The middleware-based approach introduces a structured and modular architecture composed of five interdependent layers that work collaboratively to efficiently managed complex queries in the immutable blockchain ledger and enhance query optimization in blockchain-based systems [356, 475] (see Figure 3.2).

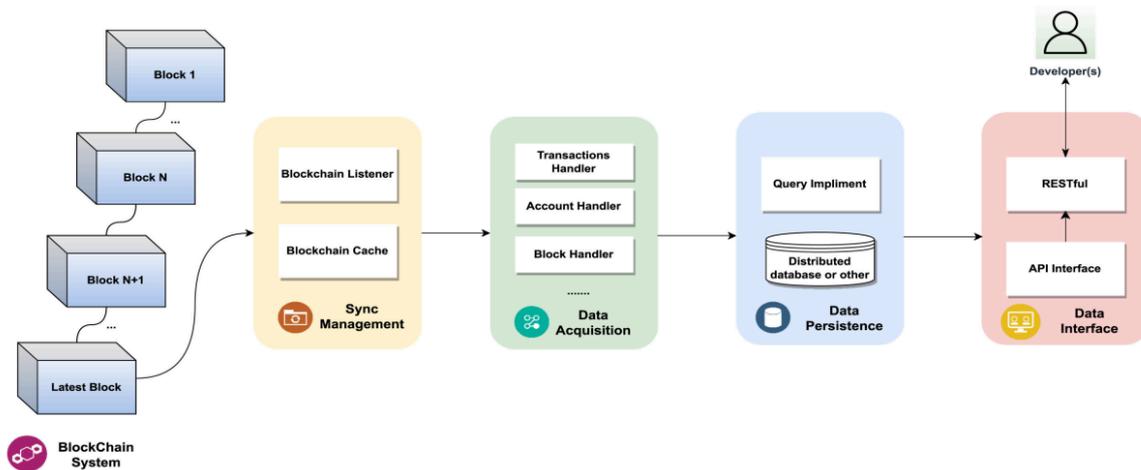


FIGURE 3.2: Architecture of middleware-based approaches [468]

1. **Synchronization Management Layer:** This first layer is responsible for monitoring the blockchain ledger and capturing newly added data (e.g., blocks and transactions), ensuring that the middleware system aligned with the latest state of the blockchain.
2. **Data Acquisition Layer:** Once new data is detected by the synchronization layer, this layer facilitates the structured extraction of relevant information from the blockchain. It responsible for parsing and filtering transaction data, smart contract states, and block metadata to ensures that only relevant data is acquired which minimizing unnecessary overhead.
3. **Data Persistence Layer:** After acquisition, the extracted data is processed and stored in a distributed or external database system (e.g., relational, NoSQL, or time-series databases).

This layer plays a central role in indexing and organizing data to support high-performance queries. It is also responsible for ensuring data consistency, integrity, and fault tolerance in the storage.

4. **Data Interface Layer:** Also known as the communication layer, it exposes unified access points for end-user applications and services to execute optimized queries, retrieve filtered results, and integrate external tools.

Blockchain Databases

Blockchain databases represent an advanced solution of data storage designed to address the limitations of standard blockchains in handling complex queries. These systems combine the immutable and decentralized nature of blockchain with the flexible querying capabilities of traditional databases. For example, BlockchainDB [112] is designed based on blockchain principles such as data sharding, a transaction manager, and a verification manager to support parallel processing, ensure data consistency, and maintain secure, tamper-proof logs. Similarly, EthernityDB [159] brings relational-like operations into Ethereum via smart contracts and a lightweight storage engine, significantly reducing execution costs for inserts and supporting familiar database operations. HBasechainDB [332], built on the Hadoop ecosystem, leverages HBase's high throughput and consistency to enhance data retrieval and filter efficiency. Another blockchain database named SolsDB [448] offers a blockchain-specific storage engine focused on optimizing Ethereum's state data management with a log-structured design and a robust verification layer to support fast, low-latency operations.

By adopting these databases, interactions with large data sets become faster and more flexible, making them ideal for applications that require high data integrity and efficient traceability queries [114].

Big Data Integration

Big data integration with blockchain technology introduces a powerful solution for optimizing blockchain queries by combining the high-performance data processing capabilities of big data techniques with the distributed computing features of blockchain systems. A notable example is presented in [60], which employs MapReduce techniques to efficiently extract and analyze data from the Ethereum platform which performs a full scan of the blockchain and inserts the extracted data into a centralized database to support in-depth analysis, including smart contract debugging and bug tracking. In this setup, the Map function retrieves blocks based on their index, while the Reduce function aggregates and stores the results in a relational database such as PostgreSQL. Furthermore, insights from SQL-based big data environments contribute valuable concepts to blockchain systems by exploring advanced query optimization techniques in SQL databases, such as multi-level indexing, query rewriting, and dynamic execution plans [319]. These two approaches highlight the importance of integrating big data solutions with blockchain to enable scalable and parallel execution of traceability queries across large datasets.

3.2.2 Based on Smart Contracts

In the context of query optimization, smart contracts can be deployed on blockchain platforms with predefined conditions that automatically execute and search for relevant events and actions

based on the terms of a contract or agreement, enabling faster and more efficient traceability queries without the need to scan the entire blockchain ledger [417, 424]. In addition their integration supports:

- Automation of verification processes such as compliance checks or conditional data access, reducing manual overhead and enhancing system efficiency [421].
- Smart contracts ensure query results remain transparent and auditable through built-in cryptographic proofs [245].
- Cost control through gas optimization for frequently executed queries [266].

By embedding indexing and querying logic directly within smart contracts, it becomes possible to dynamically filter data and respond to complex queries in real time, while preserving decentralization and trust guarantees [85, 118]. Several studies demonstrate how smart contracts, beyond their traditional transactional role, are evolving into powerful tools for executing real-time queries in decentralized systems. For instance, [5] introduced smart contract models to improve data retrieval in ride-sharing contexts by dynamically adds or updates contracts to enhance retrieval speed, demonstrating how smart contract logic can be optimized for query efficiency. Expanding beyond a specific domain, [393] proposed a smart contract-based query engine compatible with both Ethereum and Hyperledger. Further innovations were demonstrated by Chishti et al. [82], who integrated smart contracts with Merkle Patricia Tries (MPTs) for direct on-chain access to multiple transaction parameters. In the healthcare domain [143], a smart contract was designed on Ethereum to store and query pharmacogenomics gene-drug interaction data which demonstrated significant gains in scalability and query efficiency by reducing the number of entries required for large datasets, thereby streamlining the querying process. However, several factors affect this method, including query processing time, inherent vulnerabilities of smart contracts and architectural limitations of the Ethereum platform. Similarly, the approach in [150] embedded a relational database within an Ethereum-based blockchain system to support SQL-like queries directly on smart contracts and regular transactions, eliminating the need for external databases and enabling efficient range queries with significantly improved retrieval performance up to 22× faster while maintaining low memory usage.

3.2.3 Based on Indexing Techniques

While previous approaches to managing blockchain queries have improved traceability queries in blockchain systems, they often involve trade-offs related to decentralization, real-time performance, and added execution or synchronization overhead, particularly in industry applications like supply chains, and healthcare [36, 369]. In contrast, indexing technique based methods can be integrated into blockchain architectures, offering balanced and hierarchical indexing that is ideal for range queries and ordered traversal of blocks and transactions [239, 418]. These structures help minimize search latency, reduce storage overhead, and enhance the overall efficiency of traceability queries which directly integrated within the blockchain ledger without relying on external systems [267]. Moreover, in the context of the food supply chain, this improvement significantly strengthens traceability query that improve food safety control by enabling faster access to product history, early detection of contamination sources, and real-time verification of compliance at various stages.

While some indexing structures have been integrated into blockchain systems to enhance query efficiency, their application has largely remained confined to on-chain and intra-block search

levels, focusing primarily on optimizing access within individual blocks or transactions. For example, inherent structures of blockchain such as Merkle Trees in Bitcoin [414] and Merkle Patricia Tries (MPTs) in Ethereum [264], are primarily used to ensure data integrity and immutability. However, recent approaches have adapted or extended these structures to support efficient query processing. In [211] modify the Merkle tree to be the Adaptive Balanced Merkle Tree (AB-M Tree) that dynamically adjusts layers based on query demands, supporting faster verification and search. Similarly, [108] proposes a hybrid approach by combining B-trees and Skip-lists, where B-trees improve disk-based access while Skip-lists enable efficient in-memory traversal. These solutions focus on optimizing intra-block data access by reducing the need for linear scanning of transaction lists [299]. However, scalability across a large number of blocks and inter-block search performance remain unexplored with indexing techniques.

To provide a clearer understanding of the comparative advantages of different query optimization methods in blockchain systems, particularly in the context of food supply chain management, a detailed comparison of the three major approaches is presented in Table 3.1.

Features	External Databases	Smart Contracts	Indexing Techniques
Query Performance	High (off-chain processing)	Moderate (gas-limited execution)	High (on-chain optimized)
Real-time Processing	Limited (sync delays)	Good (event-triggered logic)	Excellent (direct access)
Scalability	High storage, low sync scalability	Limited (computation limits)	Moderate to high (hybrid possible)
Integration Complexity	High (requires external systems)	Medium (contract deployment needed)	Low to Medium
Maintenance Overhead	High (external upkeep)	Medium (contract updates)	Low (native to blockchain)

TABLE 3.1: Technical comparison of query optimization approaches

3.3 Blockchain Query Level: Inter-block and Intra-block

The traceability query process in blockchain systems can be divided into two main types, each applied at a different level of the ledger [102]. Inter-block queries operate at the block level, where the blockchain contains a large number of blocks and the identification of the relevant blocks within a specific time or event range presents a significant challenge, as it often requires sequential scanning across blocks [246, 416]. Intra-block queries, on the other hand, are performed at the transaction level within individual blocks, aiming to efficiently locate target transactions without scanning all transaction records in a block [449]. These two areas inter-block and intra-block querying form a comprehensive, multi-level approach to optimizing traceability queries in blockchain systems, determining where and how optimization can be integrated to improve

traceability performance and search efficiency in the blockchain ledger. Table 3.2 provides a detailed comparison between these two types.

Criteria	Inter-block	Intra-block
Target Layer	Block-level metadata (timestamps, hashes, batch IDs)	Transaction-level data within blocks
Search Scope	Reduces search volume by filtering irrelevant blocks	Precise transaction retrieval within identified blocks
Performance Benefit	Improves scalability by minimizing block accesses	Reduces latency for transaction-level queries
Use Case Example	Traceability queries by date range across multiple blocks	Retrieving specific record IDs within a known block
Limitations	Growing maintenance overhead; Requires frequent metadata updates	Increases block storage size; Complex design for diverse formats

TABLE 3.2: Comparison between inter-block and intra-block levels

3.3.1 Intra-block

Intra-block search within the blockchain focuses the query operation at the transaction level, confined to a single block. Since each block can contain hundreds or even thousands of transactions, locating a specific transaction can become computationally intensive if the system relies on a linear scan of all transactions within the block [463]. Optimization techniques provide a search complexity more efficient than linear search and provide lookup times address this inefficiency by organizing transaction data within each block to enable faster and more targeted access [232]. For example, some advanced techniques embed lightweight indexing technique within each batch of transactions that is useful in real-time traceability applications, where stakeholders require immediate access to batch-level information to validate compliance or respond to recalls [463]. By optimizing the intra-block process it is possible to improve query accuracy, reduce processing time, and enhance data granularity.

3.3.2 Inter-block

The Inter-block type focuses on optimizing the query process across multiple blocks in the blockchain ledger at the blocks level. As the number of blocks increases over time, performing linear scans to locate relevant data such as transactions from a specific range or product batch becomes increasingly inefficient and time-consuming, often requiring $O(n)$ sequential scans across all blocks [378]. To overcome this limitation, the optimization techniques in this type act as a high-level map that helps to identify which blocks are relevant to a query, thereby eliminating the need to scan the entire chain [35]. For example in food supply chain scenarios, such indexing can accelerate contamination source tracking by quickly narrowing the search to a specific block range, enabling range-based or time-filtered queries [347]. Furthermore, techniques like SCATC [439], which uses a subchain mechanism to reduce the number of scanned blocks, have shown improvements in inter-block query performance by minimizing time overhead. Overall, the

query optimization on inter-block level significantly enhances scalability, reduces query latency, and improves system responsiveness making it essential for large blockchain-based traceability systems.

3.4 Indexing Technique Fundamentals

Efficient data retrieval plays a critical role in modern systems, especially those dealing with large volumes of information such as supply chains, IoT platforms, and blockchain-based applications [88]. As datasets grow in size and complexity, conventional full-scan querying becomes impractical. To overcome this, indexing techniques are employed to optimize query performance, reduce latency, and improve data accessibility [214]. They work by building special data structures known as indexes that speed up query operations and minimizing the amount of data that needs to be scanned without scanning the entire dataset [37]. The architecture of an indexing system is not only defined by the index structure, but is composed of three main modules: Data Collection and Preprocessing, Index Structure Design, and Query Processing. Figure 3.3 illustrates the key components of the indexing system.

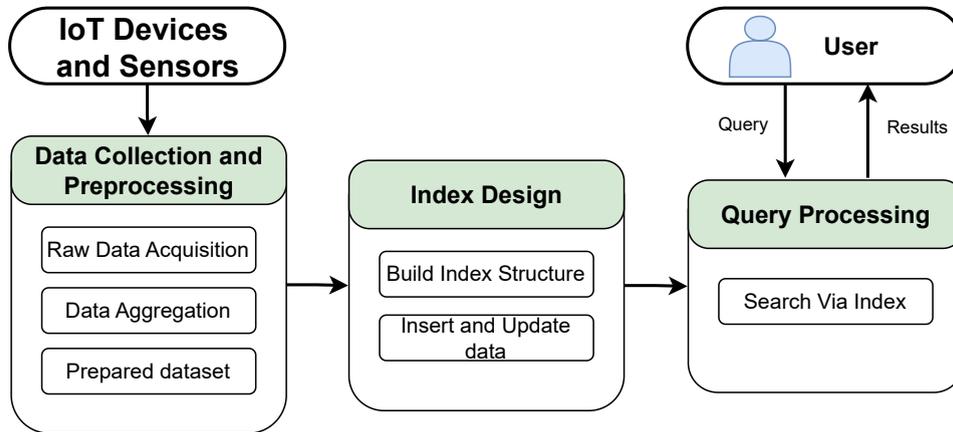


FIGURE 3.3: Overall architecture of indexing system

1. **Data Collection and Preprocessing:** The accuracy and consistency of collected data are critical, as the effectiveness of the indexing process depends on the quality of the dataset, which often integrates technologies like IoT for automated and real-time data acquisition. This data is typically sourced from various systems and may vary in format and structure, requiring preprocessing steps such as filtering, aggregation, and integration to ensure it is suitable for analysis [342].
2. **Index Structure Design:** The design of the index structure is based on commonly used models such as B-trees, hash tables, and inverted indexes each offering distinct advantages in terms of speed, memory efficiency, and implementation complexity [200]. Serving as the core of the indexing system, it enables fast retrieval by organizing keys in a way that avoids scanning the entire dataset [8]. In dynamic environments like the food supply chain, where data is continuously generated (e.g., transactions, sensor readings), the index must also support efficient updates, inserting new entries, removing outdated ones, and rebalancing the structure as needed [44].

3. **Query Processing:** Query processing is the final step in the indexing technique, performed by the requesting users whether machines, services, or human operators in traceability applications [331]. It enables efficient access to traceability data by optimizing the search process across large datasets using the index structure. This involves range queries, keyword searches, or filtering based on metadata [458].

In our work, we are particularly interested in the indexing structure and query processing aspects, especially in the context of large-scale data within food supply chain systems.

3.4.1 Indexing Technique Definition and Objectives

In the era of big data and complex distributed systems, indexing techniques have become essential for enabling efficient and scalable data retrieval and addresses critical challenges related to search speed, data volume, and accuracy [373]. Several study present key definitions of these techniques from the literature:

- According to Garcia-Molina et al. indexing in Database Systems is:

"a data structure technique used to quickly locate and access the data in a database without having to search every row in a database table each time a database table is accessed."

— Garcia-Molina et al. [128]

- Silberschatz et al. in Database System Concepts define indexing as:

"A mechanism to efficiently support access paths for various queries using additional structures that reduce the search space for requested data."

— Silberschatz et al. [355]

- Additionally, the efficiency of indexing techniques is confirmed in large-scale systems. For instance, Saidu et al. explain:

"Indexing has long been used to improve the speed of relational database systems, and choosing an adequate index at design time is critical to the database's efficiency."

— Saidu et al. [333]

Based on these definitions from different domains, we define indexing in the context of our work as follows:

"A data management strategy that enables systems to rapidly locate specific data elements using defined keys or attributes. It relies on specialized data structures called indexes to organize, optimize, and accelerate search operations within large datasets, eliminating the need for full scans, which are often time-consuming and computationally expensive."

—[61, 269, 353]

In our blockchain-based food supply chain system, indexing techniques support real-time search and data management for several objectives:

- **Storage Optimization:** Minimizing redundancy and eliminate the need for full data scans.
- **Update and Maintenance Efficiency:** Ensure that data insertions, deletions, and updates are performed without compromising system performance.
- **Scalability:** Support the growing volume, velocity, and variety of data, particularly in large-scale or distributed environments such as blockchain networks.

3.4.2 Indexing Technique Types

To support efficient data retrieval indexing techniques are implemented using different structures, each introduced to address the challenges posed by large-scale data in complex systems. These structures are specifically designed to optimize particular types of queries, balance performance trade-offs, and manage issues related to storage efficiency, update complexity, and search speed. In this section, we propose a taxonomy of these techniques and explore the most prominent index structures, including tree-based indexes (e.g., B-trees and their variants), hash-based indexes, bitmap indexes and other structures (see Figure 3.4). Additionally, we provides a comparative overview of these indexing structures and evaluates their effectiveness in addressing data retrieval challenges.

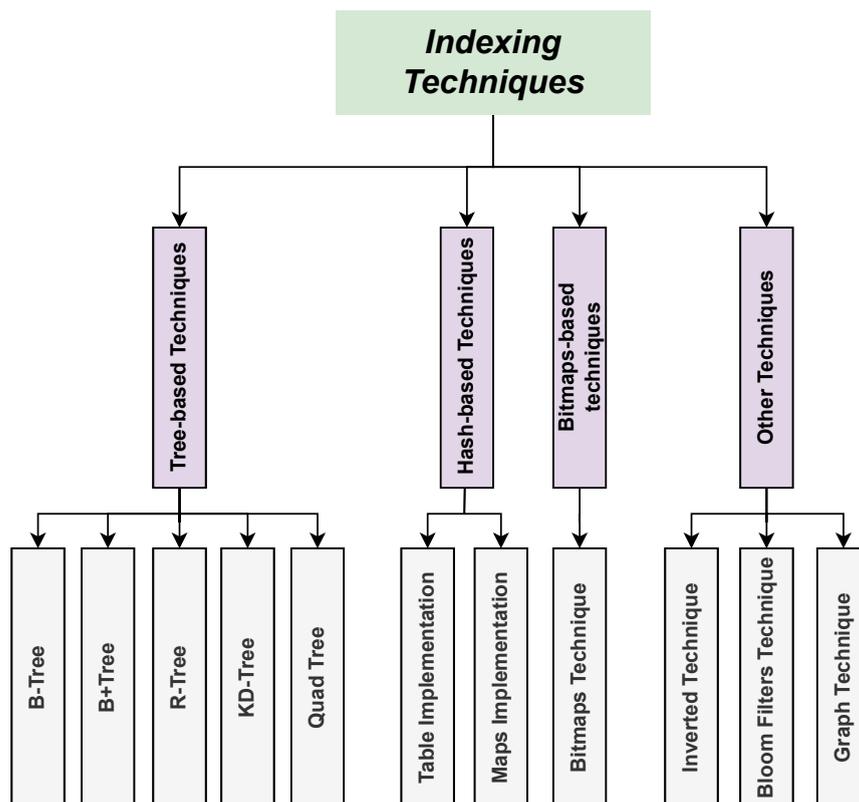


FIGURE 3.4: Classification of indexing techniques [200]

Hash based Structure

Hash-based indexing is a widely adopted technique that uses hash functions to map keys directly to storage locations, providing fast, constant-time access ($O(1)$) for exact-match queries, which particularly valuable for systems with large volumes of static or uniquely identifiable data [30, 249, 300]. However, hash indexes are less effective in scenarios requiring range queries or ordered traversal, as their structure does not preserve data order. The core components of the hash-based indexing technique include three main elements (see Figure 3.5):

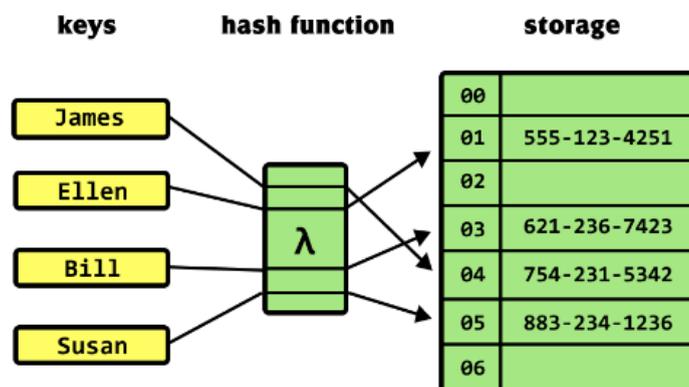


FIGURE 3.5: Hash-based indexing [336]

- **Hash Function:** The hash function takes an input key and computes a fixed-size hash value and distribute keys uniformly across the index to minimize collisions and maintain query speed. Common cryptographic hash functions such as SHA-256 may also be used to preserve data integrity alongside indexing.
- **Hash Table:** Stores the mapping between hash keys and corresponding data pointers and acts as the actual index. When a query is issued with a key, the hash function computes the hash value, and the table provides immediate access to the matching data.
- **Key-Value Pairs:** Each entry in the hash table typically consists of a key-value pair, where the Key is the hashed output derived from an attribute and the value is the pointer or metadata that indicates where the actual data resides.
- **Collision Resolution Mechanism:** The Chaining and open addressing strategies, to manage situations where multiple keys are mapped to the same location.

Hash-based indexes can be implemented in various forms, including hash maps, hash tables, and more advanced optimized variants, all designed to support efficient operations in large-scale, decentralized environments like blockchain systems.

1. **Hash Table:** A hash table is one of the most basic and efficient hash-based indexing structures uses a hash function to map keys to specific locations (buckets) in memory, allowing for constant-time lookup, insertion, and deletion operations on average [327]. Its main advantage lies in speed and simplicity, making it ideal for applications that require rapid access to specific key-value pairs like blockchain traceability systems which quickly

retrieve records by transaction ID ensuring fast access without scanning the blockchain sequentially [124]. However, This structure are not ideal for range queries or data requiring sorted access.

2. **Hash Maps:** This type is similar to a hash table but is often implemented with dynamic memory allocation and additional features such as collision resolution mechanisms [130]. Hash maps offer significant benefits for decentralized applications where real-time responses are critical, such as traceability queries in blockchain-based food supply chain systems. For instance, they can be used within smart contracts or off-chain services to link transaction IDs to their metadata or status, enabling efficient search operations without traversing the entire chain. This minimize overhead while providing flexibility and efficiency in data retrieval [318].

In the context of blockchain technology, hash-based indexing is particularly effective for optimizing traceability query, where individual transactions must be retrieved quickly within a block and enables rapid access to transaction data by mapping transaction hashes to their precise locations within the blockchain ledger [427].

Tree based Structure

Tree-based indexing structures are among the most versatile techniques used in data indexing, organizing data hierarchically in a sorted manner to support efficient range queries, ordered traversal, and dynamic data updates, while maintaining logarithmic time complexity ($O(\log n)$) for insertions, deletions, and searches [174, 177]. In the blockchain context, tree-based indexes are widely integrated to optimize traceability queries, particularly when users need to consult data over specific time intervals (e.g., tracing contamination events across a time range or filtering products by category or status). These structures offer strong performance guarantees and flexibility, making them necessary for building efficient and scalable data retrieval mechanisms in both traditional and blockchain-based systems [101]. Tree-based indexing techniques include a diverse range of structures such as B-tree, B+ tree, B* tree, R-tree, R+ tree, Quad-tree, KD-tree and Segment tree, among others. In this section, we focus on the most prominent and widely adopted variants due to their relevance and effectiveness in supporting indexing and querying in blockchain-based and food supply chain contexts (see Table 3.3).

1. **B-tree and B+ tree:** B-tree and its variant B+ tree are widely used indexing structures in database systems. A B-tree is a self-balancing multi-way tree that ensures logarithmic time complexity for insertions, deletions, and lookups and then B+ Tree structure comes to improve the B-tree by storing all actual data values in the leaf nodes and linking these leaves for efficient range queries [303]. This two types of tree structure can be used to index data transactions in the blockchain ledger by supports efficient range-based searches, such as retrieving all food records between two dates or within a specific date range which offer excellent read/write balance and adaptability for growing datasets. Additionally, it scale well with large datasets and support incremental updates, making them suitable for dynamic supply chain environments [284].
2. **R-Tree:** R-Tree is a hierarchical data structure derived from the B+ Tree, commonly applied for organizing and querying multidimensional data, such as spatial or temporal attributes and data of n-dimensions by generating several small minimum bounding rectangles (MBR) and reduce dead spaces that is very efficient for range requests [144]. In the

Structure Type	Query Support	Complexity	Advantages	Disadvantages
B-Tree	Point queries, range queries	$O(\log n)$	Balanced read/write performance; suitable for dynamic datasets	Less optimized for sequential access;
B+ Tree	Range queries, sorted access	$O(\log n)$	Efficient range search; leaf-level data linked for fast traversal; scalable	Additional overhead for maintaining leaf node links
R-Tree	Spatial and range queries (multi-dimensional)	$O(\log n)$ average, worse in degenerate cases	Ideal for spatial/geographic data; supports spatial filtering	Performance degrades with overlapping MBRs; complex insertion
Quad Tree	Spatial queries, range and point queries in 2D space	$O(\log n)$ average	Good for geospatial indexing; supports fast 2D filtering	Only suited for 2D; not optimal for high-dimensional data

TABLE 3.3: Comparison of tree-based indexing structures [200]

food supply chain, R-trees structure can be used for applications involving geolocation-based traceability like tracking product movement from farms to distribution centers [237]. Queries in this tree offer spatial filtering capabilities, making them ideal for integration with GIS systems or IoT sensor networks that provide location-aware food tracking. However, they face several limitations in terms of increased space, time, and computational complexity due to overlapping multiple MBR regions, which can degrade search performance [144].

3. **Quad Tree:** A Quad Tree is a multidimensional indexing structure that recursively partitions a two-dimensional space into four quadrants or regions, where each internal node has exactly four children (leaf nodes) which enables efficient spatial decomposition and access to data distributed across a plane [229]. In the context of food supply chain traceability, quad trees are particularly well-suited for managing and querying geospatial data, such as tracking product movements across all supply chain stages with rapid range queries and spatial filtering, which are essential when identifying contamination zones or assessing localized production issues [225]. Additionally, in blockchain-based systems, Quad Trees have been integrated with smart contracts and off-chain services to support efficient querying of location-specific transactions, making them a valuable indexing technique in blockchain applications [243].

Bitmap based Structure

Often referred to as BitArray or vector-based indexing, this structure efficiently represents the presence or absence of attributes in a dataset through binary vectors (bitmaps), enabling faster

search and retrieval in large databases and data warehouses (DW) with reduced complexity [72]. A typical bitmap index structure is a very efficient technique for answering complex queries which consists of bitmaps for each attribute value, a mapping table for record identifiers, and a bitwise operation engine to process the queries. The main advantages of bitmap indexing include its simplicity, low search complexity, and high performance in read-only or low-update environments such as data warehouses [80]. However, its main disadvantage lies in its inefficiency with frequently updated datasets, as bitmaps may need frequent rewriting, leading to performance degradation. In the context of blockchain-based food supply chains, bitmap indexing can be beneficial when integrated with off-chain databases like cloud and IPFS which allows fast filtering and retrieval of products based on batch IDs, food safety certifications, temperature compliance, or supplier attributes [486].

Other Structures

In addition to the previously discussed structures, other data structures such as inverted indexes, Bloom filters, and graph-based structures can also be effective to illustrate indexing concepts and offer high performance in specific data environments.

1. **Inverted Indexes:** Inverted indexes, widely used in search engines and document retrieval systems, map attributes to a list of document or data identifiers, enabling fast keyword or exact-match queries [254]. For example, in a blockchain-based food certification system, an inverted index can link keywords like “organic,” “halal,” or “gluten-free” to corresponding product batches or transaction IDs which facilitates rapid filtering of food items based on certification attributes stored off-chain. However, they are more suited to unstructured text data and less effective for time-based or range-based queries typical in food traceability systems [261].
2. **Bloom Filters:** Bloom filters are probabilistic data structures that offer highly space-efficient membership testing. They are beneficial for quickly checking if an element might exist in a dataset, with the trade-off of false positives. Bloom filters have been integrated with blockchain to support lightweight query filtering, but their approximate nature makes them less suitable for traceability scenarios where precision and completeness are critical [362].
3. **Graph-based Indexes:** Graph-based indexing design data as nodes and relationships and is beneficial for complex interrelated data, such as social networks or semantic web applications [203]. For instance, for blockchain based food supply chain case the system in [432] model records and data chunks as a bipartite graph to optimize parallel record search which reduces the query time overhead. Although graph-based indexes are promising, they introduce cost and complexity that may not be compatible with the linear, chronological nature of blockchain transaction records in food supply chains [447].

3.4.3 Query Types

As various indexing techniques enhance the performance of data retrieval operations and are integrated into a wide range of applications, query types have become another essential component for supporting diverse data formats. Modern applications collect massive volumes of real-time data in structured, semi-structured, and unstructured forms. This diversity highlights

the importance of query types, as a wide variety from simple exact-match queries to complex analytical and semantic queries has emerged, each with distinct performance requirements and access patterns. This section provides a comprehensive overview of the principal query types.

3.4.3.1 Point Queries

Point queries, also known as exact-match queries, are the most basic used type in database systems retrieving data records that exactly match a given key or value [301]. This query type is well supported by hash indexes and B-Tree indexes due to their ability to locate target values through deterministic paths, offering fast retrieval speeds and minimal resource consumption especially when the indexed value is unique [23]. Point queries are not based on similarity measures but rather on identity comparison, using a binary evaluation that reflects the strict matching requirement characteristic of this query type:

$$\text{Match}(x, y) = \begin{cases} 1 & \text{if } x = y \\ 0 & \text{otherwise} \end{cases}$$

Point queries are typically used in systems that require fast retrieval based on simple keys, such as in a food supply chain that needs to search for a food product by its unique identifier, retrieve specific data records, or identify data fraud, but they offer limited flexibility, as they cannot handle partial matches or range searches [33].

3.4.3.2 Range Queries

Range queries involve retrieving data where a specified attribute falls within a given range which improves analytical and time-series applications by offering an efficient traversal of sorted data and support for ordered access [139]. There are many indexing techniques support this type of query such as Tree-based structures like B-trees and B+-trees, as they preserve order among indexed values. Range queries are not based on similarity metrics, but instead rely on interval inclusion logic, which checks whether a data point lies within the specified range. This logic can be formalized as:

$$\text{Match}(x, [a, b]) = \begin{cases} 1 & \text{if } a \leq x \leq b \\ 0 & \text{otherwise} \end{cases}$$

This type of query is widely used in time-series databases [478], healthcare data analysis [235], and blockchain systems [228] to retrieve all data within a certain date range or filtering records readings that fall within storage limits. Despite their benefits, range queries can be less efficient in hash-based indexing systems and may incur higher overhead when large ranges are involved or data is distributed.

3.4.3.3 Keyword/Search Queries

Keyword query types are used to index unstructured or semi-structured data, enabling the search for records containing specific terms or text fragments" [79]. These queries are commonly supported by inverted indexes or full-text search engines, which enable efficient retrieval in

large text-based collections [433] and can be used in different system like healthcare [260] and blockchain [104] to search about data descriptions, locate records and identify transactions tagged with specific terms. This query type is based on partial or approximate matching rather than exact equality, and its similarity is typically evaluated by comparing the overlap between the set of query keywords and the set of keywords in the target data. A widely used formula for measuring this similarity is the Jaccard similarity, defined as [290]:

$$\text{Similarity}(Q, D) = \frac{|Q \cap D|}{|Q \cup D|}$$

Where:

- Q : Set of query keywords
- D : Set of keywords in the target record/document

The value ranges from 0 to 1, with higher scores indicating greater keyword overlap. Despite their flexibility, keyword queries can face challenges, such as dealing with synonyms, typos, and relevance ranking when working with multiple keywords.

3.4.3.4 Aggregation Queries

Aggregation queries are designed to process and summarize large volumes of data by applying mathematical or statistical operations such as counting, summing, averaging, finding minimum or maximum values, or grouping data based on specific attributes [199, 406]. Supported by bitmap indexes and tree-based indexes, these queries enable fast aggregation over large datasets, especially when the data is partitioned and complex [454]. For example, in the food supply chain context, aggregation queries can be used to calculate the average storage temperature of perishable goods, count defective batches, or total daily shipment volumes [420]. These insights support decision-making for quality control, logistics optimization, and compliance monitoring and can vary depending on data distribution, index type, and system architecture, particularly in real-time or blockchain-based environments where aggregation must be efficiently performed over distributed data. Aggregation queries do not rely on similarity measures but they involve mathematical operations applied over sets of values. However, when comparing aggregated values across groups (e.g., comparing average temperatures between facilities), statistical distance or deviation measures such as Euclidean distance can be optionally used. For instance:

$$\text{Distance}(x, y) = \sqrt{(x - y)^2}$$

Where:

- x, y are the values being compared.
- Represents the Euclidean distance between two scalar values.

This type of comparison is typically part of post-aggregation analysis, not the underlying query itself. Therefore, the concept of similarity does not necessarily apply to aggregation queries, unless it is extended to include comparative evaluation.

3.4.3.5 Semantic Queries

Semantic queries are designed to retrieve information based on the meaning, context, or relationships between entities rather than relying on exact matches or syntactic structures [464]. This type of queries are typically supported by graph-based indexes, ontology-enhanced inverted indexes, or knowledge graphs, which can represent hierarchical relationships, synonyms, and contextual associations [73, 379]. In the context of the food supply chain, semantic queries might be used to identify all products containing allergens by recognizing their ingredients [153], or to connect suppliers based on geographic proximity, shared certifications, or transport conditions [270]. Such queries enhance traceability, safety compliance, and decision support in complex distributed networks.

To evaluate relevance in semantic queries, similarity measures are often employed, particularly in vector space models where both the query and indexed documents are embedded into semantic vector spaces. Cosine similarity is one of the most common metrics used, and is calculated as:

$$\text{CosineSimilarity} = \cos(\theta) = \frac{A \cdot B}{\|A\| \|B\|}$$

Where:

- A and B are the vector representations (e.g., food item descriptions)
- $A \cdot B$ is the dot product of vectors A and B
- $\|A\|$ and $\|B\|$ are the Euclidean norms (magnitudes) of the vectors

Higher cosine similarity indicates a stronger semantic match between the query and the target data, allowing systems to retrieve relevant results even when terms are lexically different. Despite their effectiveness, semantic queries pose challenges related to computational costs, ontology coordination, and scalability, especially in real-time or blockchain-based environments, where maintaining consistency across distributed nodes is critical.

3.4.3.6 Top-K Queries

Top-K queries are used to retrieve k of the most relevant results from a dataset based on a specific scoring or ranking criterion [169]. They are commonly used in applications such as product recommendations, supplier rankings, or selecting the best-performing distribution routes [78]. Indexing structures, such as multidimensional trees (e.g., R-tree and KD-tree), are used to support efficient Top-K retrieval, especially when dealing with large, high-dimensional datasets. These indexes help reduce the search space and improve performance by focusing only on the most relevant parts of the data [483]. The relevance or similarity in Top-K queries is often computed using a scoring function that combines multiple weighted attributes. A typical example is:

$$\text{Score}(i) = w_1 \cdot a_1(i) + w_2 \cdot a_2(i) + \dots + w_n \cdot a_n(i)$$

Where:

- $a_1(i), a_2(i), \dots, a_n(i)$ are attribute values for item i (e.g., delivery time, price, rating)

- w_1, w_2, \dots, w_n are corresponding weights reflecting user-defined importance
- The score represents a weighted linear combination of attributes

Records with the highest scores are ranked at the top and returned as the query result. In some cases, cosine similarity, Euclidean distance, or domain-specific utility functions are used, depending on the context and nature of the data. However, challenges arise for this type of query in dynamic datasets, where frequent updates can affect the accuracy of the evaluation and require re-evaluation of the classifications, resulting in performance impairments.

Based on previous studies, each query type meets specific needs, and choosing the appropriate type significantly impacts system performance, scalability, and data retrieval efficiency. Therefore, a clear understanding of the differences between them is essential for choosing the most appropriate approach in a given context. To better understand the differences between the various query types, Table 3.4 provides a comparative overview based on key characteristics.

Query Type	Performance	Best For	Limitations
Point	Fast ($O(1)$ - $O(\log n)$)	Exact key lookups Transaction verification	No partial/range support
Range	$O(\log n + k)$	Time-series data Expiration tracking	Inefficient for wide ranges
Aggregation	$O(1)$ pre-computed	Quality metrics Supply chain KPIs	High update overhead
Keyword	$O(m)$ term length	Text search Product descriptions	Requires text indexes
Semantic	Graph traversal cost	Category navigation Nutrition analysis	Complex setup
Top-K	$O(k \log n)$	Supplier rankings Performance benchmarks	Frequent updates hurt

TABLE 3.4: Comparison of query types in indexing systems

3.4.4 Evaluation Metrics: Search Performance, Update Performance, Storage Overhead

Selecting the appropriate indexing techniques in data retrieval systems requires balancing system requirements where the read-intensive systems prioritize query efficiency, while write-intensive applications require indexing methods that support fast updates with minimal overhead [119]. To determine the most appropriate indexing strategy, evaluation metrics must be carefully considered based on three key criteria: query efficiency (the speed and responsiveness of read operations), storage overhead (the additional memory or disk space required by the index), and update performance (the cost of insert, delete, and modify operations). Understanding these metrics helps align indexing choices with system goals, particularly in data-intensive domains such as blockchain networks and food supply chain systems.

Search Performance

Query efficiency is a metric that represents the performance of an indexing technique in terms of the search time required to retrieve relevant data from a dataset in response to a specific query [242]. This metric primarily focuses on query response time, typically measured based on latency (the time taken to return query results), while often neglecting throughput (the number of queries processed per unit of time) and I/O operations, especially in systems where read operations dominate [194]. To provide a clearer analytical perspective, query efficiency (QE) can be mathematically modeled as the inverse of the total query response time (T_q):

$$QE = \frac{1}{T_q}, \quad \text{and} \quad T_q = T_{\text{access}} + T_{\text{I/O}} + T_{\text{processing}}$$

Where:

- T_{access} : Time to traverse or locate data using the index structure
- $T_{\text{I/O}}$: Disk or memory access time (depends on the number of page accesses)
- $T_{\text{processing}}$: Time to process and return results

The evaluation of indexing techniques in data retrieval systems generally involves measuring the average or worst-case response time, which depends on several factors such as the type of index, the structure of the data, query type, data distribution, and system architecture. Some indexing techniques demonstrate strong performance in query efficiency, for instance, B+ Tree indexes offer logarithmic query times, support sorted access, and are well-suited for range queries. In contrast, hash indexes provide constant-time lookups but lack ordering capabilities, making them less suitable for range-based queries. Therefore, selecting an appropriate indexing method based on query efficiency is critical to achieving high performance in large-scale systems (see Table 3.5).

Indexing Technique	Query Types	Search Performance
Hash	Point queries	O(1) average
B-Tree	Point and range queries	O(log n)
B+ Tree	Range and sequential queries	O(log n)
Quad Tree	2D spatial queries	O(log n) average
KD Tree	Multidimensional points	O(log n) average
R-Tree	Spatial range queries	O(log n) average
Bitmap	Low-cardinality attributes	O(1) per bit
Inverted Index	Text/search queries	O(1) term lookup
Bloom Filter	Membership tests	O(k) operations
Graph Index	Graph traversals	O(V+E)

TABLE 3.5: Search performance of indexing techniques

Update Performance

The update performance of the indexing technique refers to the efficiency to handles different data operations, including insertions, deletions, and updates where the performance of the indexing technique is to minimize latency and resource consumption associated with maintaining index structures during such operations. This metric is typically evaluated by measuring the time cost of maintaining the index after a data change and the overhead caused by re-balancing, or restructuring operations and several factors influence this metric, including the complexity of the index structure, data distribution, update frequency, and support for concurrent operations. The update performance metric consider the cost of index maintenance under varying conditions can be modeled as:

$$C_{\text{update}}(n) = \sum_{i=1}^u \left[\alpha_i \cdot C_{\text{insert}}(n) + \beta_i \cdot C_{\text{delete}}(n) + \gamma_i \cdot C_{\text{modify}}(n) \right]$$

where:

- n : Number of entries in the index.
- u : Total number of update operations.
- $C_{\text{insert}}(n)$: Insertion time complexity.
- $C_{\text{delete}}(n)$: Deletion time complexity.
- $C_{\text{modify}}(n)$: Modification time complexity.
- $\alpha_i, \beta_i, \gamma_i \in [0, 1]$ with $\alpha_i + \beta_i + \gamma_i = 1$

This formula provides a flexible model for evaluating update performance based on workload characteristics and the structural behavior of the indexing technique. For example, B+ tree indexes can be computationally expensive in write-intensive workloads due to rebalancing operations, while hash indexes provide fast updates but face challenges such as collision handling and hash table resizing. Therefore, choosing an indexing method with robust update performance is essential to ensure real-time data integrity and operational continuity in systems with frequent updates (see Table 3.6).

Storage Overhead

Storage overhead refers to the additional memory or disk space required to store and maintain indexing structures alongside the original dataset. Its primary goal is to evaluate the cost-effectiveness of an indexing technique in terms of the amount of additional space it consumes compared to the performance benefits it offers. This overhead includes both metadata associated with the index (such as pointers, keys, or tree nodes) and auxiliary structures used to facilitate fast data retrieval [465]. The storage overhead (denoted as SO) can be expressed as a relative ratio between the total size of the dataset including the index (S_{total}) and the size of the original dataset without indexing (S_{data}):

$$\begin{aligned} \text{SO} &= \frac{S_{\text{total}} - S_{\text{data}}}{S_{\text{data}}} \\ &= \frac{S_{\text{index}}}{S_{\text{data}}} \end{aligned}$$

Indexing Technique	Update Performance
Hash	Fast updates $O(1)$ average case (require rehashing)
B-Tree	Moderate speed $O(\log n)$ (maintains balance during updates)
B+ Tree	Slower than B-Tree $O(\log n)$ (require leaf node maintenance)
Quad Tree	Moderate speed $O(\log n)$ (require tree restructuring)
KD Tree	Moderate speed $O(\log n)$ (high dimensions)
R-Tree	Complex updates $O(\log n)$ (bounding box adjustments)
Bitmap	Slow updates $O(n)$ worst case (requires full modifications)
Inverted Index	Moderate speed $O(\log n)$ (requires list updates)
Bloom Filter	Fast updates $O(k)$ for k hash functions
Graph Index	Slow updates $O(V+E)$ (complex relationship maintenance)

TABLE 3.6: Update performance of indexing techniques

Where:

- S_{total} = total size of the system (data + index).
- S_{data} = size of the original dataset.
- S_{index} = space consumed by the index alone.

Several factors influence SO value, including the type of indexing technique, the cardinality of the indexed attributes, and the redundancy of stored values. For example, bitmap indexes may incur high storage overhead when applied to high-cardinality attributes due to the large number of bit vectors generated. Hash indexes are generally more compact but may require additional space for collision handling. On the other hand, B+ Tree indexes offer a balance between query efficiency and storage cost, though they still involve overhead from node structures and pointers. The study of this metric is essential, especially in storage-constrained or private environments such as blockchain systems or edge computing and the indexing strategy must align with the system scalability requirements without compromising the integrity and efficiency of operations (see Table 3.7).

Indexing Technique	Storage Overhead
Hash	Low to moderate (additional hash table)
B-Tree	Moderate (pointers and balancing data)
B+ Tree	Moderate-high (pointers and leaf nodes)
Quad Tree	High (2D spatial partitioning metadata)
KD Tree	Moderate (k-dimensional splitting)
R-Tree	High (MBR)
Bitmap	Very high (bit arrays for all values)
Inverted Index	Moderate to high
Bloom Filter	Low (hash functions)
Graph Index	Very high (node/edge storage)

TABLE 3.7: Storage overhead of indexing techniques

3.5 Conclusion

This chapter presented the final part of our context, demonstrating how, where, and which indexing structures can be effectively integrated to optimize traceability queries and ensure food safety in the blockchain-based food supply chain application. Our work specifically falls within the field of blockchain technology, an emerging solution that enhances big data management in the food supply chain by providing greater transparency and trust in traceability processes. While blockchain offers numerous advantages, we also identified its inherent limitations, particularly the inefficiency of traditional sequential query methods. We began by analyzing the evolution of query management in blockchain systems, highlighting the transition from traditional approaches, such as external databases and smart contract-based approaches, to the emergence of indexing structures. Furthermore, by categorizing the query process into inter- and intra-block levels, we developed a structured understanding of performance bottlenecks and identified how to strategically apply indexing techniques at each level. Finally, we explored the fundamentals of indexing techniques for choosing the appropriate structure, including basic types such as hash-based, tree-based, and point map indexing, along with key evaluation metrics such as query time, space overhead, and update complexity.

Part II

Contributions

CHAPTER 4

B-TREE INDEXING APPROACH IN BLOCKCHAIN-BASED FOOD SUPPLY CHAIN TO IMPROVE TRACEABILITY QUERY

Chapter contents

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4.1 Introduction and Research Questions

The food supply chain faces numerous challenges, particularly in ensuring food safety and maintaining effective traceability. The integration of blockchain technology into this domain has brought significant benefits, including transparency, data immutability, and improved traceability. However, one of the main limitations of blockchain-based systems lies in the efficiency of query processing, especially when retrieving traceability data across multiple blocks.

In this chapter, we aim to address these limitations by integrating the B-tree indexing technique with blockchain to propose a novel blockchain-based traceability system that optimizes traceability queries, particularly inter-block queries. This integration enables the identification and retrieval of only the relevant blocks that contain the required data, eliminating the need to scan the entire blockchain ledger. As a result, inter-block query processing is optimized, significantly enhancing the efficiency of traceability queries.

To guide this contribution, we formulate a set of research questions that address the core challenges related to the efficiency of traceability queries in blockchain-based food supply chain systems and define the improvements and objectives of our proposed solution. Table 4.1 presents the research questions discussed in this chapter.

4.2 Related Works

The emergence of blockchain technology has provided an innovative solution for ensuring food safety in supply chains, using multiple technologies, particularly traceability. In this contribution, we review blockchain-based traceability systems and discuss various studies aimed at improving the performance and efficiency of traceability queries.

4.2.1 Blockchain-based Traceability Systems in the Food Supply Chain

To highlight the significance of blockchain technology in ensuring data traceability within the food supply chain, several systems have been proposed into multiple area, each highlighting relevant systems according to their purpose.

RQs	Research Question	Key Improvement
RQ1	How can indexing be combined with blockchain technology to improve query performance for cross-block traceability in food supply chain systems?	Design a hybrid architecture where indexing technique is externally integrated with blockchain to filter and locate relevant blocks based on time-range keys.
RQ2	What is the most suitable indexing structure for supporting inter-block and range-based queries in a blockchain-enabled food supply chain?	Evaluate and justify the use of B-tree structure as a balanced indexing method suited for ordered and range-based access across distributed blockchain data.
RQ3	To what extent does B-tree indexing improve the scalability and retrieval time of traceability queries compared to traditional sequential scanning methods across large blockchain datasets?	Improve query scalability by eliminating full-chain scans and retrieving only the blocks matching the index ranges, reducing lookup time.
RQ4	How does the B-tree indexing approach compare to other blockchain-based query optimization methods in supporting complex and range-based traceability queries?	Enable efficient range-based queries by using fabrication time as index keys, outperforming unstructured or flat search techniques.

TABLE 4.1: Research questions and key improvements

1. **General Blockchain-based Traceability Systems:** Several studies have proposed general frameworks integrating blockchain to enhance data traceability in the food supply chain. For instance, Pal et al. [298] examined the role of blockchain in IoT-enabled food distribution networks. Their work highlights how blockchain improves food labeling integrity and helps manage quality and contamination risks in food logistics. Similarly, Xu et al. [441] proposed a system known as OriginChain, which replaces a centralized database with blockchain to provide high-availability traceability data. In another study, Maity et al. [256] integrated blockchain into the production stage to improve traceability and transparency. Their solution promotes secure data sharing among stakeholders by addressing information protection and interoperability challenges.
2. **Blockchain-based Traceability Systems for Specific Food Products:** Blockchain has also been applied to specific product categories to improve traceability. Morais et al. [280] developed a blockchain-based traceability platform for fruits and vegetables. Their system enables end-to-end tracking of perishables, allowing consumers to verify key information such as product origin and harvest dates. In the dairy industry, Casino et al. [70] introduced a decentralized system using smart contracts and Ethereum to ensure food safety, meet regulatory standards, and improve consumer trust. The solution offers a complete framework for traceability in dairy supply chains. For the fishery sector, Patro et al. [304] implemented a private Ethereum-based blockchain system to address traceability shortcomings and fraud prevention. Their solution uses smart contracts and validated algorithms to automate and secure seafood tracking from source to consumer.
3. **Blockchain-based Traceability Systems for Agricultural Products:** Improving traceability in agricultural supply chains has also been a focus of several studies. Yao et al. [452] proposed a blockchain system integrated with IPFS for agricultural product traceability. This Ethereum-based solution improves data reliability and addresses leakage

issues common in centralized systems. Zhang et al. [473] designed a dual-chain blockchain system for cold chain logistics in fresh agricultural products. Their approach improves traceability authenticity and reliability for both consumers and regulators. Another work by Zhang et al. [472] introduced a traceability model for the grain and oil supply chain using trusted identification methods and Hyperledger Fabric to solve data sharing and security challenges. Furthermore, Zhang et al. [474] developed a blockchain storage layer enhanced by machine learning-based anomaly detection to improve the reliability of traceability data.

4. **Blockchain-based Traceability Systems for Consumers Restrictions:** Traceability using blockchain technology is also beneficial for ensuring compliance with consumer-specific restrictions. For example, in [190], blockchain is applied in medical diets for continuous monitoring and self-care of diabetic patients. Using IoT sensors, the platform records blood sugar levels on an immutable Hyperledger blockchain with a novel, scalable, and high-performance consensus model called Proof-of-Review (PoR), enabling secure and transparent health data tracking. Another study in [382] focuses on halal requirements by developing a web-based halal traceability system that utilizes blockchain technology to monitor halal compliance throughout the chicken meat supply chain. The system employs permissioned protocols to securely record product transfers and certification data, and uses distributed ledgers to demonstrate the tracking of product status, highlighting the potential of blockchain to enhance halal integrity.

4.2.2 Blockchain Traceability Query Optimization Systems

Although blockchain offers numerous advantages for traceability systems in the food supply chain, there are still challenges with the efficiency of traceability queries. Consequently, many researchers have conducted relevant studies that address the challenge of long response times for data queries in blockchain systems, aiming to better understand how to improve query efficiency within the blockchain.

The first significant work [178] introduces a new storage layer in the blockchain called Adaptive Balanced Merkle Tree (ABM tree). This structure combines a balanced binary tree with a Merkle tree to improve storage scalability and facilitate intra-block querying of historical data. Similarly, the work in [330] proposes the LineageChain system, which enables better query performance and minimal storage. It uses blockchain technology with a novel indexing structure based on a deterministic append-only skip list (DASL) to improve the efficiency of blockchain traceability queries. An improved version of the LineageChain system is proposed in [360]. This version introduces two new indexing models, namely: TDASL (Two-tier Deterministic Append-only Skip List) and PPBPT (Predefined Partition B-plus Tree). These models aim to improve historical queries in multidimensional data, by improving query capabilities and storage efficiency. However, they require additional construction and update time. In [233], the authors address the efficiency issues of blockchain data queries by introducing flexible query interfaces for Ethereum blockchain data, such as range and top-k queries, which are not supported by the native Ethereum client. The B+ tree has also been used to improve search capabilities and reduce storage costs [437]. Implemented on the Ethereum Geth 1.8 client, it supports top-k, range, and equality searches in real time, demonstrating efficient search functionality and low storage costs. To support efficient intra-block queries, recent research suggests replacing the Merkle tree with a new query scheme that includes additional fields in the block header. This method allows for optimizing inter-block queries, achieving high execution efficiency with minimal storage [217]. Another study introduces the Subchain-based Account Transaction Chain (SCATC), which divides the blockchain into subchains to reduce the search path for inter-block

queries. This approach minimizes access to irrelevant blocks, as only the last block of each sub-chain needs to be queried [439]. Further improvements to traditional blockchain query methods have been proposed to enhance search efficiency for both inter- and intra-block queries [239]. The proposed method uses a novel data structure within the Hyperledger Fabric framework, incorporating two indices: an Abstract-Trie index for efficiently querying original data features and an Operation-Record List index that links operation records to their corresponding data. To decrease query times within blocks and improve user experience in blockchain-based electronic trading systems, modifications to the B-tree structure were introduced within the Ethereum framework, utilizing a B-Key-Value index directory to store transaction and block numbers as key-value pairs [415]. Another approach enhances search efficiency for traceability in critical areas, such as food and pharmaceuticals, by transforming the query into a graph-searching problem that uses parallel searching with a maximum matching algorithm [432]. In [140], a dual-layer index structure is introduced in blockchain technology. This structure combines a B+ tree index with a Merkle tree to optimize intra-block queries and modifies the data structure with an index table to improve inter-block queries, thereby enabling efficient traceability within blockchain systems. This proposed structure improves the efficiency of traceability queries compared to the original blockchain, while also reducing storage requirements and construction time. To enhance security and privacy, the authors in [218] propose a blockchain-based traceability system that employs an independent index with cloud computing for secure data storage and fine-grained access control, thereby improving the search efficiency of data stored on the blockchain. A recent study [456] proposes on-chain data scalability through a storage scheme based on transactions and smart contracts. This method aims to improve inefficient querying of IoT data stored on the blockchain by implementing a Skip-list index, which allows for logarithmic time searches and reduces storage overhead.

Many previous systems have primarily focused on enhancing internal queries within blocks by adjusting the blockchain data structure and incorporating new indexing techniques to replace the Merkle tree. However, they often overlook queries and the time consumed in traversing between blocks, which are crucial for retrieving desired blocks, especially in complex food supply chain scenarios with a large number of blocks.

4.3 Proposed Model

This section provides a detailed description of the system architecture and design aspects, outlining the specific details of blockchain technology, B-tree index, and the optimized traceability query process, along with their impact on improving data traceability in the food supply chain context.

4.3.1 System Architecture

The proposed system aims to address the query problems of traditional blockchain systems, which primarily rely on analyzing the entire blockchain ledger. This approach improves traceability queries while preserving the unique properties of blockchain technology. In the context of food safety, blockchain acts as a distributed ledger and storage layer, allowing for the storage of comprehensive information and data related to food products at various stages of the supply chain. The data collected through this process are organized into blocks, representing individual transactions, and linked to an external B-tree index as an indexing layer. This facilitates the

extraction of relevant blocks and improves the query process performed by consumers at the cloud layer and query interface. This layer functions as a lightweight interface that manages consumer requests, such as routing traceability queries to the blockchain framework layer, where decentralized data processing is performed, and returns responses without any central processing. Figure 4.1 illustrates the overall system architecture.

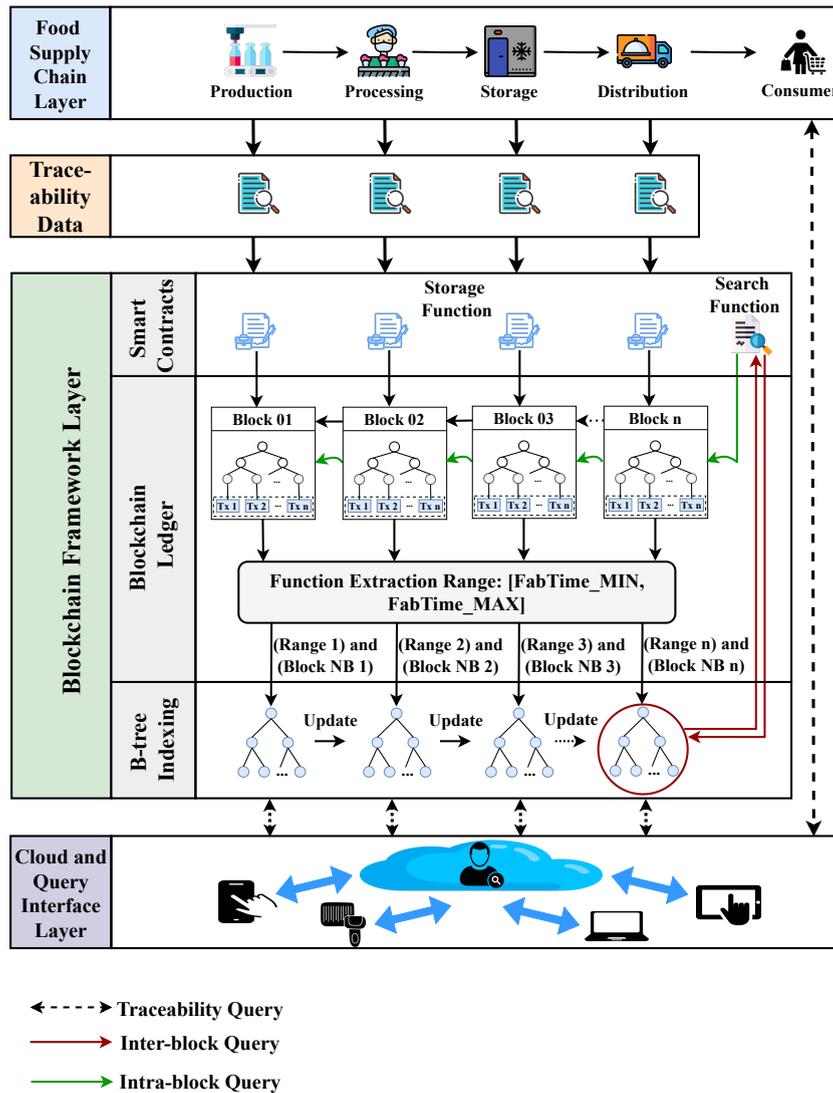


FIGURE 4.1: General architecture of the proposed system

The proposed approach consists of the following steps:

1. **Transaction Structure Modification:** The transaction data structure within each block is modified to include the fabrication time of the food product as a new attribute.
2. **Range Extraction:** For each block, the minimum and maximum fabrication times are computed from all its transactions. These values define a specific range $[FabTime_MIN, FabTime_MAX]$ that represents the temporal span of transactions within the block.
3. **Range Association:** Each computed time range is then associated with its corresponding block number, forming a pair ($[FabTime_MIN, FabTime_MAX], Block_Number$).

4. **B-tree Index Construction:** An external B-tree index, independent from the blockchain ledger, is created to store these pairs. This structure supports efficient range-based search operations.
5. **Index Update:** The B-tree index is continuously updated with each new block added to the blockchain, ensuring it accurately reflects the most current data in the network.

The external B-tree index enables efficient retrieval of relevant blocks containing traceability data from the large number of blocks, thereby queries within the blockchain ledger are restricted to these specific blocks excluding those that do not contain relevant data. Using this external index structure, blockchain-based traceability systems can experience a significant enhancement in query efficiency and overall system performance.

4.3.2 Blockchain Technology Design

In the context of the food supply chain, data related to a wide range of food products is collected and identified using unique identifiers such as barcode strings, fabrication times, expiration dates, QR codes, or other forms of identification. This data is stored in the blockchain ledger as traceability information through smart contracts in the form of transactions.

Transactions within the native blockchain are uniquely identified and structured using attributes such as Hash ID and timestamp, which effectively distinguish them within the blockchain network. In our model, given the large number of blocks in the ledger each containing numerous transactions related to various food products, we link each transaction to a specific product using the fabrication time (FabTime) as a unique identifier. This identifier is generated and associated with food products from the initial production stage to the final stage in the supply chain.

To support this, the transaction structure in our network has been updated to include additional information relevant to food products involved in the supply chain. The enhanced transaction structure in our model includes the following attributes (see Figure 4.2):

- **Timestamp:** Records the time the transaction was created.
- **Hash ID:** Uniquely identifies each transaction.
- **FabTime:** Indicates the product's fabrication time and serves as a unique product identifier used to associate the transaction with a specific food item.
- **Supply Chain Stage:** Specifies the current stage of the product in the supply chain.
- **Traceability Data:** Contains detailed information relevant to tracking and verifying the product journey.

This adjustment enhances storage capacity and improves the traceability and transparency of food products in the supply chain, facilitating the querying of traceability data within blockchain technology.

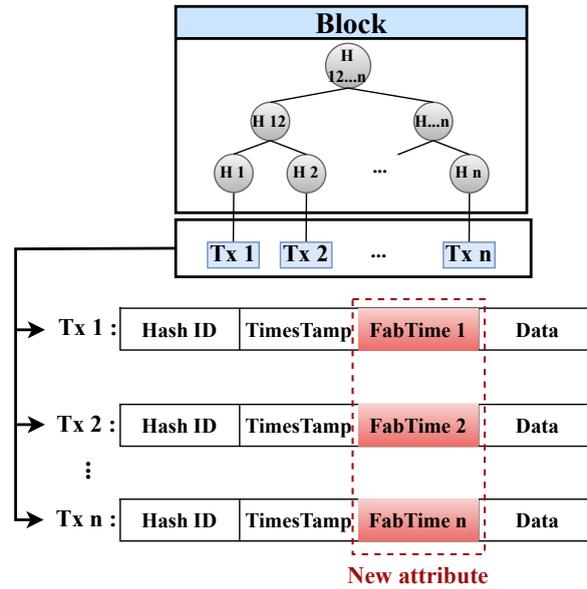


FIGURE 4.2: Design of block and transaction structure in the proposed system

4.3.3 B-Tree Index Design

This section presents a detailed implementation of the external B-tree index, which is used in our system to filter and extract target blocks containing traceability data from the large blockchain ledger. By leveraging the B-tree structure, the system enables efficient and rapid access to stored data with a logarithmic time complexity of $O(\log n)$, maintaining both integrity and performance even during concurrent updates associated with block creation in the blockchain network.

The B-tree index is constructed with the creation of the first block (genesis block) of the blockchain network and is subsequently updated with the addition of new blocks to the chain. During this process, the minimum and maximum fabrication times (FabTime_MIN and FabTime_MAX) are extracted from the transaction data within each block and stored in the B-tree structure. As each subsequent block is created, the index is updated with data extracted from the transactions within the new block (see Figure 4.3).

The primary purpose of this index is to organize and manage two key types of information: the fabrication time ranges of all blocks within the blockchain network extracted from the FabTime values of each block's transactions and the corresponding block numbers (Block NB) associated with each range. Queries to this index use the FabTime of a food product as the query key and return all block numbers whose time ranges include the given FabTime. Thus, the index efficiently provides all the relevant blocks as output for the query.

In our design, the B-tree index is generated and maintained externally to the blockchain network. It operates on the transaction data of each block without directly interacting with the blockchain ledger itself. The design process of the B-tree index consists of two main components: (1) Extraction [FabTime_MIN, FabTime_MAX] range, and (2) Construction and Update of B-Tree index. This process is illustrated below.

1. **Extraction [FabTime_MIN, FabTime_MAX] Range:** The extraction of the [FabTime_MIN, FabTime_MAX] range for a block is performed by calculating the minimum and maximum fabrication time values from all transactions within each block in the

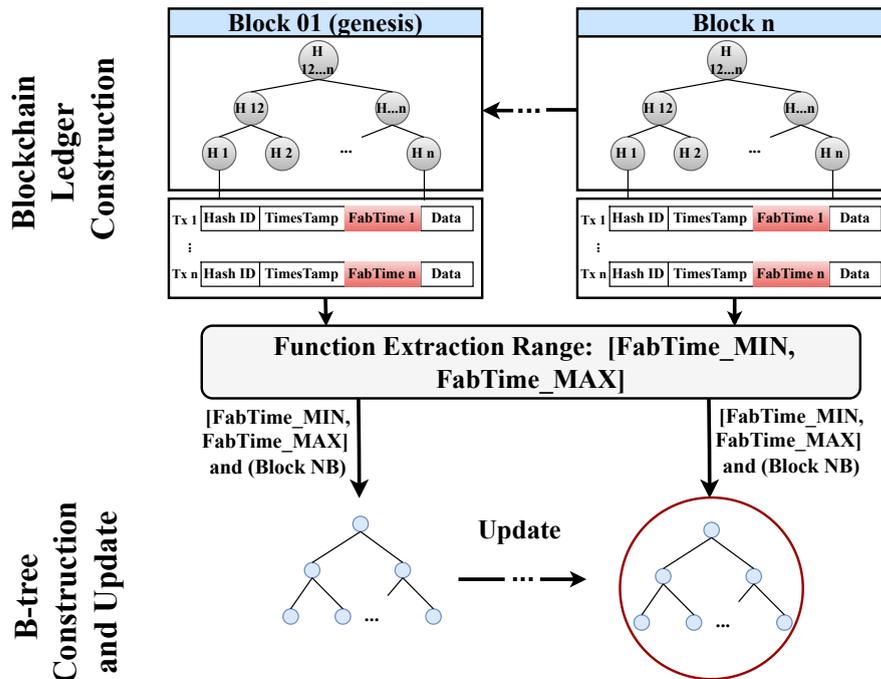


FIGURE 4.3: B-tree index design

blockchain network. The index is updated simultaneously with the creation of each new block, with each block in the blockchain network gaining its corresponding range, which is then stored as data in a B-tree index. The extraction process from the transaction data for each block is illustrated in Algorithm 4.1.

For security purposes, the extraction method occurs during the transactions proposal stage before the block is formed and added to the blockchain ledger. This allows access to the transaction data before the validation process with consensus algorithms and data encryption with the Merkle Hash Tree, enabling direct access to transaction data, including FabTime values. The range calculation is performed by a fast sorting algorithm specifically designed to iterate through all FabTime values of the transactions within each new block and determine their specific range $[FabTime_MIN, FabTime_MAX]$. This process guarantees that the index effectively captures and organizes the specific data, thereby facilitating efficient and fast data retrieval.

2. **Construction and Update of B-tree Index:** Following the range extraction process from the transaction data of the first block (genesis block), the system creates the B-tree index to store the range as key with the specific block number (Block Number=1) as its corresponding value. This B-tree index is updated with each creation of new block in the blockchain network to ensure synchronization with the latest data regarding the ranges and block numbers. When new groups of transactions are proposed, their FabTime range is compared to existing ranges within the B-tree index. This process triggers updates to incorporate new data until we find and construct the final version of the B-tree index and the blockchain ledger. The process of constructing and updating the B-tree index structure is illustrated in Algorithm 4.2.

The construction and integration of the B-tree index play a crucial role in enhancing data management and query performance within the proposed system. This mechanism is fundamental for the efficient storage, retrieval, and organization of key information specifically, fabrication

Algorithm 4.1 Extraction [FabTime_MIN, FabTime_MAX] range

Require: TXS: Transactions in the block;
Ensure: [FabTime_MIN, FabTime_MAX] range;

- 1: $FabTime_MIN \leftarrow +\infty$
- 2: $FabTime_MAX \leftarrow -\infty$
- 3: **for** each TX in TXS **do**
- 4: $FabTime \leftarrow GetFabTime(TX)$
- 5: **if** $FabTime < FabTime_MIN$ **then**
- 6: $FabTime_MIN \leftarrow FabTime$
- 7: **end if**
- 8: **if** $FabTime > FabTime_MAX$ **then**
- 9: $FabTime_MAX \leftarrow FabTime$
- 10: **end if**
- 11: **end for**
- 12: **return** [$FabTime_MIN, FabTime_MAX$]

time values and their associated block numbers. By leveraging the inherent properties of the B-tree structure, the system supports fast search and insertion operations while minimizing disk I/O [107, 187]. This indexing approach significantly improves data access by using FabTime as the primary key and ensures that the index remains up-to-date with the most recent data recorded on the blockchain. As a result, the B-tree index is dynamically maintained in parallel with updates to the blockchain ledger, supporting efficient and reliable traceability queries.

4.3.4 Traceability Query Design

The proposed traceability query process is based on blockchain ledger and B-tree external index, with these two components the search for historical data is optimized within the food supply chain system. The complete process of a traceability query in our system, from the consumer query to retrieving traceability data is presented in the sequence diagram in Figure 4.4, illustrating all interactions among system components and details of both type of search query inter-block and intra-block.

The query process on the external B-tree index retrieves blocks containing data about the food product, returning block numbers as values with FabTime as the query key. Subsequently, the query in the blockchain ledger focuses on retrieving traceability data only from the identified blocks in the initial step ignoring the blocks that do not contain traceability data. The traceability query in the B-tree index and the blockchain ledger is detailed in Algorithm 4.3 and Algorithm 4.4.

These two parts of our system enhance the efficiency of data traceability queries and improve historical data searches in the food supply chain compared to the original, traditional methods that involve scanning all blocks within the blockchain network.

4.4 Experiments

The proposed system was implemented and tested on a simulator that takes into consideration the blockchain technology. This section presents a detailed evaluation of our approach that uses

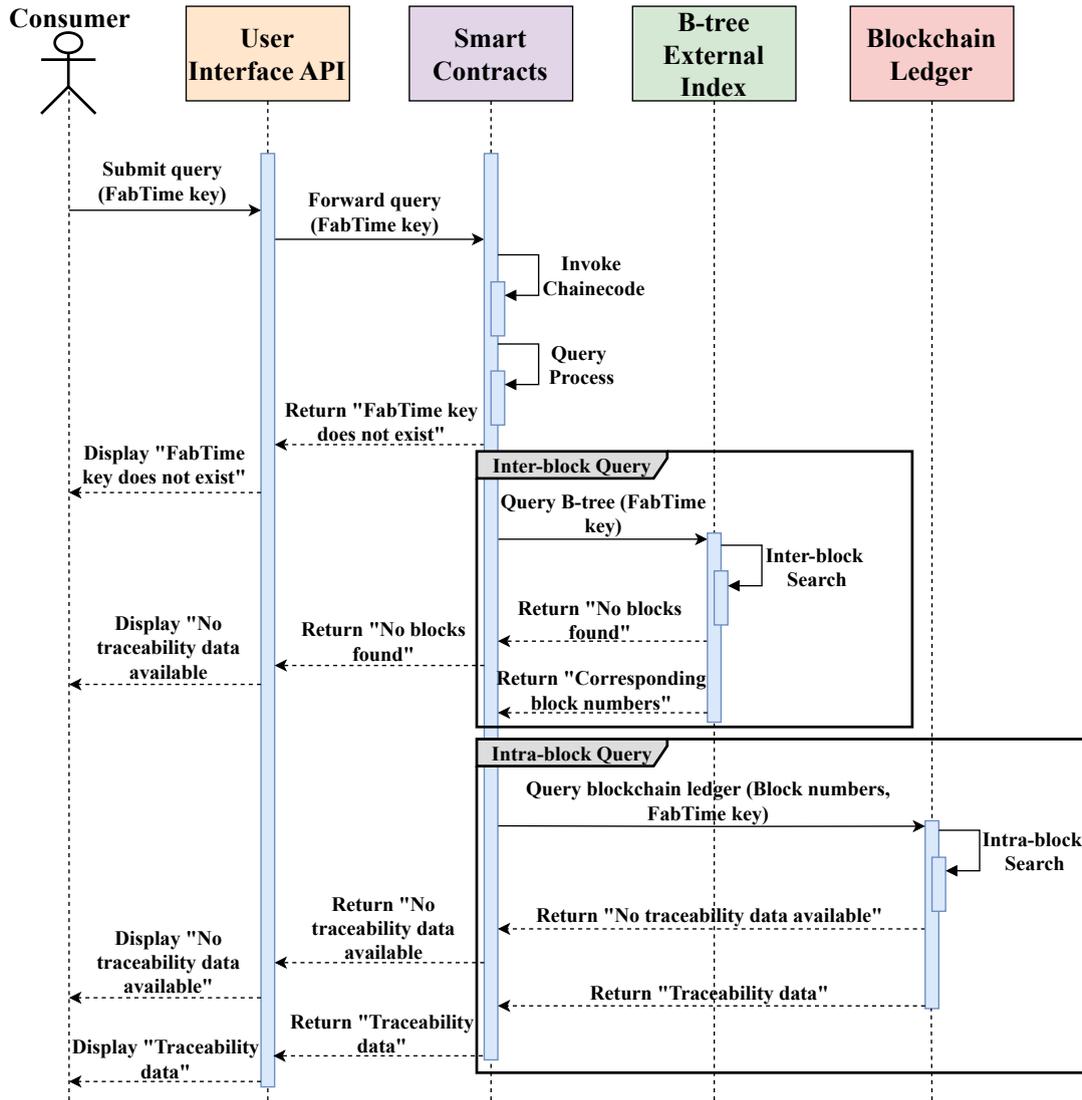


FIGURE 4.4: Sequence diagram illustrating the traceability query process in the proposed system

in the system is presented in Table 4.2. The Hyperledger Fabric framework allows managing the current state of the keys, as well as a history of all changes to each key over time using two types of databases, namely LevelDB and CouchDB. To enable real-time measurements when querying for historical transactions, the history of the database is turned off, and the index methods of K-V pairs within it are disabled. This action makes it possible to query the on-chain ledger instead of using the history database and its indexing method, thereby providing insights into how the ledger size affects system performance. Additionally, we opted for CouchDB as the storage location for the B-tree external index.

Before designing and deploying the test network, several modifications were made to the framework to ensure it was compatible with the proposed design. Before designing and deploying the test network, several modifications were applied to ensure compatibility with the proposed design. The process involved the following main steps:

1. **Test Network Setup:** The test network was established based on the standard procedures provided by the Hyperledger Fabric framework.

Algorithm 4.3 Traceability query in B-tree index

Require: FabTime: Query key;
Ensure: Relevant_Blocks: Block numbers;

- 1: *Relevant_Blocks* \leftarrow Empty List
- 2: **for** each [*FabTime_MIN*, *FabTime_MAX*] in *B-tree* **do**
- 3: **if** *FabTime* \geq *FabTime_MIN* **and** *FabTime* \leq *FabTime_MAX* **then**
- 4: *BlocksNB* \leftarrow *B-tree.getBlocksNB*(*FabTime*)
- 5: *Relevant_Blocks.append*(*BlocksNB*)
- 6: **else** *FabTime* Not exist ▷ Key does not exist
- 7: **end if**
- 8: **end for**
- 9: **if** *Relevant_Blocks* is Empty **then**
- 10: **return** \emptyset ▷ No blocks containing traceability data
- 11: **else**
- 12: **return** *Relevant_Blocks* ▷ Return block numbers as results
- 13: **end if**

Algorithm 4.4 Traceability query in blockchain ledger

Require: FabTime, Relevant_Blocks (block numbers from B-tree index): Query key;
Ensure: TraceData: Traceability data;

- 1: *TargetBlocks* \leftarrow *GetTargetBlocks*(*Relevant_Blocks*) ▷ Obtain block numbers from B-tree
- 2: **while** *TargetBlocks* is not Empty **do**
- 3: *TraceData* \leftarrow *SmartContractQueryFunction*(*TargetBlocks*, *FabTime*) ▷ Smart contract query function with block numbers and FabTime as arguments
- 4: **if** *TraceData* is not Empty **then**
- 5: *TraceDataToConsumers*(*TraceData*)
- 6: **else**
- 7: **return** *TraceData* = \emptyset ▷ No traceability data available
- 8: **end if**
- 9: **end while**
- 10: **return** *TraceData* ▷ Return traceability data as results

2. **Smart Contract Customization:** The smart contract (Chaincode.go) was modified to include new functions tailored to the requirements of the system. This involved initializing the blockchain ledger with 20 food products, each having six attributes, one of them is the fabrication time as a key attribute for each product.
3. **Storage and Query Functions:** These functions provide a way to build and query the blockchain ledger using SDK tools. In our test network, we specifically use the GetKey-History function to retrieve the historical data of a given key as a baseline method, which is then compared to our proposed B-tree index-based approach in terms of search time complexity.

To better test the performance of the proposed method, three scenarios with varying conditions were proposed. Each one has a different parameter configuration that can influence query performance. The parameters used to configure the datasets for each scenario include:

- **Target Blocks Size:** This parameter signifies the number of blocks within the network that contain data and information pertinent to our query. It defines three scenarios within our experiment and has a significant influence on the search time of the query.

Feature	Description
Framework	Hyperledger Fabric
Version	2.2.14 (LTS)
Language	Go
Network Type	Permissioned
Consensus	Raft (Crash Fault Tolerant)
Smart Contract	Chaincode in Go
Architecture	Modular, pluggable components
Privacy	Private data collections, channel isolation
Ledger	Blockchain log + World state
Use Case	Food supply chain traceability

TABLE 4.2: Overview of Hyperledger Fabric configuration in the proposed system

- **Blockchain Size:** This parameter denotes the number of blocks within the blockchain network, influenced by the complexity of the chain and the volume of data in the supply chain. We have generated various sizes of blockchain for our experiments.
- **Data Size:** Represents the size of data transactions that can be stored in each block. We can set the data size in the configuration file 'Configtx' of the simulator by the parameter 'MaxMessageCount' to control the number of transactions that can be batched in each block.
- **Target Data Size:** This factor represents the size of relevant data found in target blocks, which corresponds to the number of transactions in each target block. This parameter significantly influences the query search time.

Table 4.3 provides an overview of the scenarios employed in our experimental tests with multiple parameter configurations.

	Target Block Size	Blockchain Size	Data Size
Scenario 1	1 Block	100, 200, 300, 400, 500, 1000, 2000, 3000, 4000, 5000	5 Transactions
Scenario 2	3 Blocks	100, 200, 300, 400, 500, 1000, 2000, 3000, 4000, 5000	5 Transactions
Scenario 3	10 Blocks	100, 200, 300, 400, 500, 1000, 2000, 3000, 4000, 5000	5 Transactions

TABLE 4.3: Scenarios and parameters configuration

The experimental test is conducted on Mint Ubuntu operating system. The hardware configuration used for the blockchain test network includes an Intel Core i5-5200U processor running at 2.2 - 2.7 GHz, with 4 GB of DDR3 L-1600 RAM.

4.4.2 Results and Analysis

In experimental tests conducted using the Hyperledger Fabric simulator, search queries are performed in two methods based on the product key: the standard method and the B-tree index-based method. The search process within our simulator is executed by the peer node after deploying the smart contract code and invoking the query function within it. This query process undergoes a series of steps before entering the blockchain ledger, including signature verification and network access control for security purposes.

Once the datasets are generated and the blockchain ledger is created in our test network, the process of searching for historical product data begins. The time required to search and retrieve traceability information on that product is then recorded for each method. The experiments conducted to evaluate the query process using both methods in the blockchain simulator are depicted in Figures 4.5, 4.6 and 4.7, representing scenarios 1, 2, and 3, respectively. Each figure shows the variations with a low blockchain size (100, 200, 300, 400, and 500) and a high blockchain size (1000, 2000, 3000, 4000, and 5000).

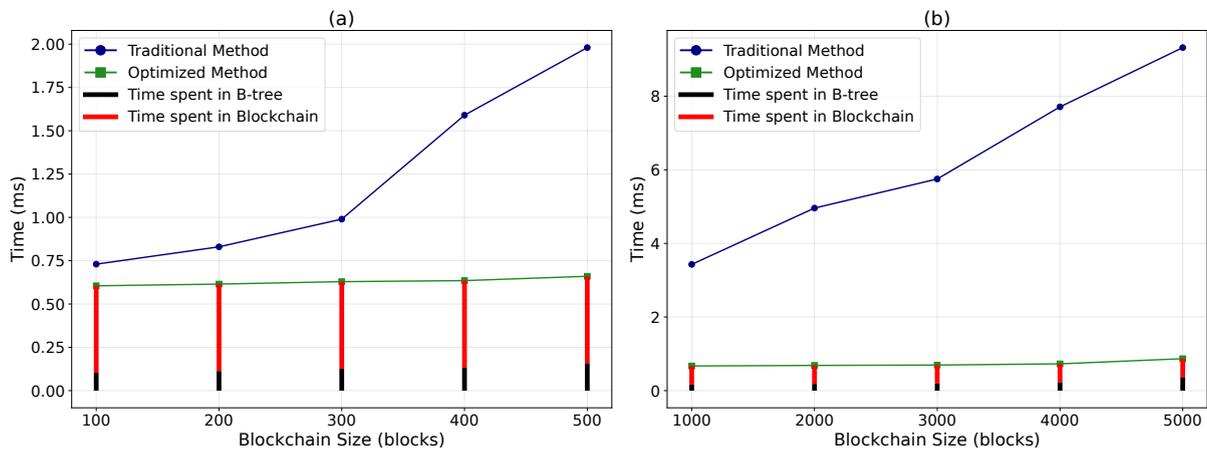


FIGURE 4.5: Performance comparison of search query under scenario 1

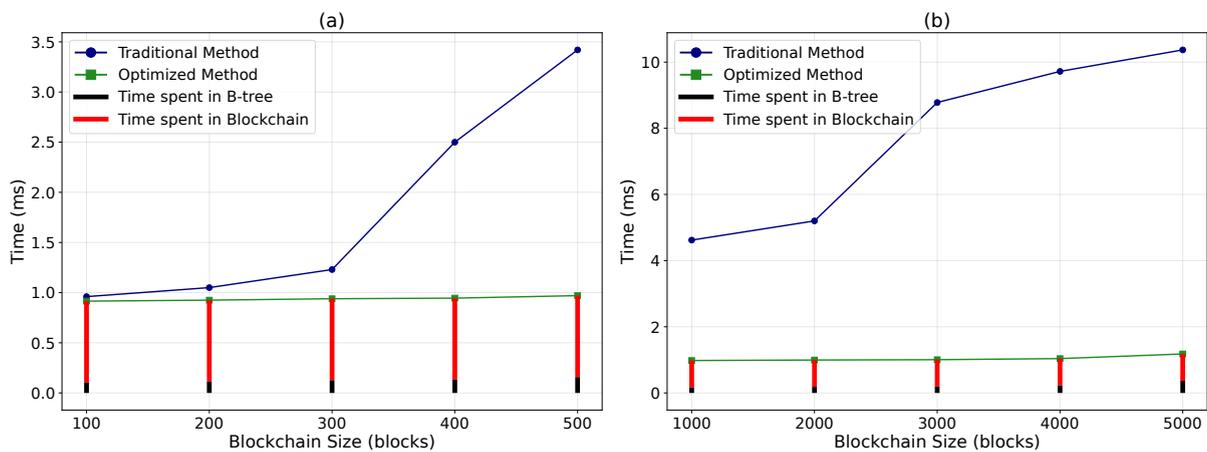


FIGURE 4.6: Performance comparison of search query under scenario 2

In Figure 4.5.a, the performance of the traditional method decreases as the blockchain size increases, resulting in longer query times for historical data, ranging from 0.73 to 1.98 ms. In contrast, the query in the proposed approach using the B-tree index, which comprises the time

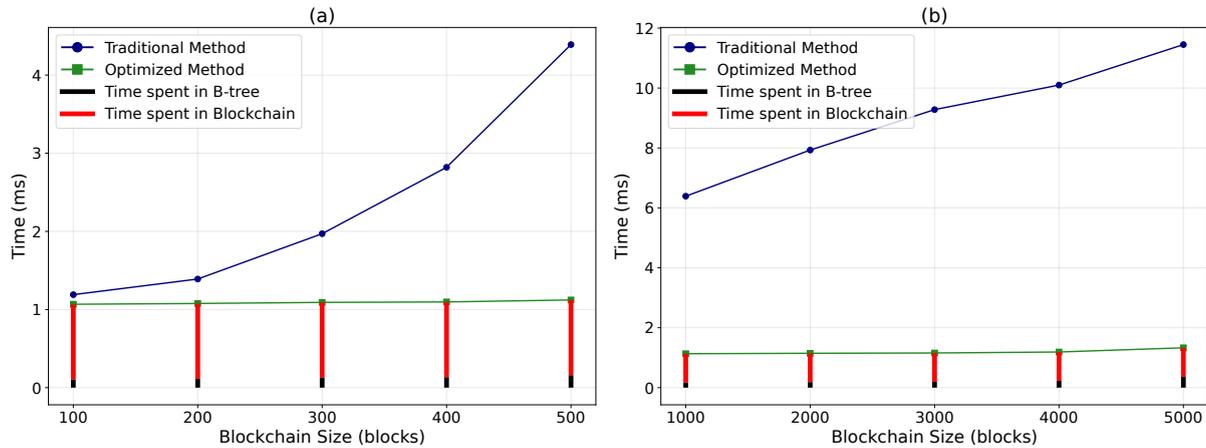


FIGURE 4.7: Performance comparison of search query under scenario 3

spent within the B-tree index (black bar) and the time spent within the blockchain ledger (red bar), demonstrates a consistently lower query time across all blockchain sizes, ranging from 0.605 to 0.660 ms. Figure 4.5.b shows that the query search time with the optimized method continues to outperform the traditional method. In these cases, the search time increases compared to the results in Figure 4.5.a because the size of the blockchain has increased between 1000 and 5000 blocks. In the traditional method, the performance of the search query ranges between 3.43 and 9.32 ms, while the optimized method performs better with a range of 0.670 to 0.868 ms.

In Figure 4.6.a, the query performance of the optimized method across all blockchain sizes ranges between 0.915 and 0.970 ms, while in the traditional method, it exceeds 3 ms. Figure 4.6.b shows that even with an increase in the number of blocks, the query demonstrates superior performance in the optimized approach with the B-tree index. In this case, the traditional method ranges between 4.62 and 10.37 ms, whereas the optimized method ranges between 0.980 and 1.178 ms. Although increasing the size of both the blockchain and the target data may affect the query search time, it does not have a significant impact on the optimized method working with the B-tree index.

In Figure 4.7, the results are larger compared to the previous scenarios due to the increase in the target block size to 10 blocks. The proposed method continues to produce favorable outcomes compared to the traditional method across all blockchain sizes. In Figure 4.7.a, the query performance in the optimized method consistently ranges between 1.067 and 1.122 ms, while the traditional method gradually increases from 1.19 to 4.39 ms. Furthermore, Figure 4.7.b shows that the query time of the optimized method consistently remains below 1.34 ms across all blockchain sizes, whereas the traditional method exceeds 6 ms and continues to increase to 11 ms in the highest case.

4.4.3 Discussion

Based on the experimental results, we observed that the Blockchain Size and the Target Data Size are two factors that significantly affect the efficiency of search query time. In the traditional method, we observed that as the number of blocks in the ledger and the size of target blocks increase, the search query time also increases. Similarly, the time also increases in the proposed method but by relatively small amounts across all scenarios.

Since the query time in the optimized method is subdivided into two components—the query time in the B-tree index (represented by the black bar) and the query time in the blockchain ledger (represented by the red bar), the results indicate that the search query time under the B-tree index structure is efficient, consistently remaining below 0.366 ms across all blockchain sizes. Conversely, the time taken in the blockchain ledger remains consistent regardless of the blockchain size.

In blockchain systems, B-tree can be applied at the block level for rapid retrieval of specific blocks across the entire ledger, while at the transaction level, it can optimize searches within each block and improve Merkle tree traversal [36]. This integration supports range queries, which is particularly beneficial in supply chain applications, where users need rapid access to accurate data across multiple stages [265]. Furthermore, the B-tree indexing technique outperforms other tracking technologies (e.g., RFID, IoT devices), that focus primarily on real-time identification and monitoring but lack efficient and scalable query processing capabilities [385]. Table 4.4 presents a comparative analysis of tracking and tracing technologies highlighting the importance and motivation to adopt B-tree indexing based on multiple features.

Feature (Functional/Technical)	RFID/IoT Devices	B-tree Indexing
Technology Type	Hardware-based (sensors, tags)	Software-based (algorithms)
Primary Purpose	Real-time tracking and sensing	Efficient data retrieval and query optimization
User Interaction	Passive (scan only)	Active (flexible queries)
Query Type Supported	Basic query (simple key)	Complex queries (range, multi-criteria, attribute-based)
Integration	Physical integration	Digital integration
IoT Layer	Device layer	Information processing layer
Data Scalability	Low (hardware memory/storage limitations)	High (efficient structure)
Data Integrity	Low (vulnerable devices)	High (cryptographic support)
Data Update Handling	Low (not ideal for frequent updates)	High (balanced structure)
Data Transparency	Low (partial access)	High (full access)
Search Time	Moderate to High (depending on scan context)	Low (logarithmic time complexity)

TABLE 4.4: Comparison of tracking and tracing technologies: RFID/IoT devices vs. B-tree indexing

We compared our system with related methods based on various factors, including blockchain platform, query type, index structure, query influencing factors, query complexity, and storage overhead. The comparison results, which highlight the advantages and best-performing aspects of our system, are summarized in Table 4.5.

In general, by integrating the external B-tree index with the blockchain ledger, we improved the traceability queries of food products in the supply chain. The proposed method skips blocks

	Blockchain Platform	Indexing Type	Index Structure	Query Influencing Factors	Query Complexity	Storage Overhead
[178]	Hyperledger Fabric	Inter-block & Intra-block	ABM-Tree	Blockchain size, Data vol./block, Network config., Hardware resources	$O(N) \sim (\log N)$	High
[330]	Hyperledger Fabric	Inter-block & Intra-block	DAS-List	Query complexity, Consensus, Network latency	$O(\log p N)$	Medium
[360]	Hyperledger Fabric	Inter-block & Intra-block	PPB+Tree, 2-tier DAS-List	State version size	$\log m N + \lceil vl/N \rceil$	High
[437]	Ethereum	Intra-block	B+tree + MHT	Data vol./ block, Query complexity, Blockchain size	$O(\log p N)$	High
[439]	Ethereum	Inter-block & Intra-block	Subchain Index, MHT + B+tree	Blockchain size, Subchains Nb., Query complexity	$O(N)$	Medium
[415]	Ethereum	Intra-block	BVK-Tree	Query complexity, Block structure, Hardware resources	NA	Medium
[140]	Hyperledger Fabric	Inter-block & Intra-block	MHT + B+Tree, Hash Table	Index structure, Query type, Blockchain size	NA	Medium
[218]	Hyperledger Fabric	Inter-block & Intra-block	MHT + B+tree, Ind. Index	Query complexity, Data volume, Indexing technique	$O(\log N)$	High
Ours	Hyperledger Fabric	Inter-block & Intra-block	B-tree external index	Blockchain Size, Data volume	$O(\log N)$	Low

TABLE 4.5: Functional comparison between existing works and the proposed system

lacking traceability data, focusing the search only on relevant blocks. This reduces the number of blocks scanned during the query process, thereby cutting down time overhead in the ledger and yielding superior results.

4.5 Conclusion

This chapter present a novel blockchain based traceability system with the integration of indexing techniques especially the B-tree index aimed at optimizing blockchain traceability queries, with a particular focus on inter-block queries. Our solution was developed within the Hyperledger Fabric framework and demonstrated significant improvements in the search time for historical data of food products compared to traditional methods. By ignoring irrelevant blocks and streamlining the query process, we enhance the efficiency of distributed traceability systems, thereby enabling faster and more reliable access to critical information. Additionally, our research underscores the potential of combining indexing techniques with blockchain technology to enhance traceability systems in the food supply chain, thus improving food safety, transparency, and consumer trust in the global food system.

CHAPTER 5

B+ TREE INDEXING AND NLP MODEL
IN BLOCKCHAIN-BASED FOOD SUPPLY
CHAIN TO IMPROVE TRACEABILITY
QUERY

Chapter contents

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5.1 Introduction and Research Questions

In addition to the limitations of current blockchain-based traceability systems in the food supply chain in terms of sequential search, they also suffer from simple key-based queries (e.g., using product IDs) through various information and communication technologies (ICT) such as bar codes, QR codes, and RFID. However, these types of query are not efficient, and these tools offer limited functionality, as they store a finite amount of data and provide a one-way interaction where consumers can only retrieve information without the ability to ask specific questions related to a specific step or obtain detailed data about the product. This limitation leads to inefficiencies and does not meet the growing consumer demand for comprehensive and timely information, especially for those with specific dietary restrictions.

In this chapter, we propose a new blockchain-based traceability system that integrates a Natural Language Processing (NLP) model and an indexing technique based on the B+tree structure. The NLP model processes consumer queries to extract the desired information and identify the specific stage of the supply chain where traceability data is required. In addition, a B+ tree index is created as a dedicated structure that stores the stages of the supply chain as keys and their corresponding block addresses as values. Our system optimizes the search process across a large number of blocks by identifying and returning the addresses of the blocks corresponding to the specific supply chain stage mentioned in the consumer's text query and intra-block queries are then performed only within these identified blocks to extract the traceability data.

Table 5.1 summarizes the specific research questions that guided this contribution, along with the key improvements presented in this study.

5.2 Related Works

Information and Communication Technologies (ICT), including various technologies, have played a significant role in enhancing traceability, real-time monitoring, and data management in food supply chains. Table 5.2 presents the most widely used technologies in food traceability systems.

Early traceability systems primarily relied on these technologies to improve operational visibility and ensure food safety. For example, Pigni and Conti [310] presented a traceability solution using NFC technology. By embedding NFC tags throughout the production process, data is captured and stored in a cloud-based database, which can be accessed via Android applications.

RQs	Research Question	Key Improvement
RQ1	How can we improve the limited use of ICT technologies that only support simple traceability queries in food supply chain systems?	Integrate an NLP model to replace basic ICT tools and enable more interactive and intelligent consumer access.
RQ2	How can we enhance the expressiveness of consumer queries to support more complex and specific traceability requests in the food supply chain?	Use NLP techniques to understand and process complex consumer queries involving multiple supply chain attributes.
RQ3	How can we overcome the inefficiency of sequential search in blockchain when ICT technologies are used alone?	Combine NLP-based query handling with an indexing mechanism based on B+ tree to accelerate traceability search in the blockchain ledger.

TABLE 5.1: Research questions and key improvements

Technology	Application in Food Supply Chain Traceability
RFID	Automatically identifies and tracks food products during transportation and storage, enhancing traceability and inventory accuracy.
QR Codes	Offers low-cost digital access to product information via scannable codes, promoting consumer interaction and data transparency.
WSN (Wireless Sensor Networks)	Collects real-time environmental data (e.g., temperature, humidity) to maintain cold-chain integrity and ensure product quality.
NFC (Near Field Communication)	Embeds secure, mobile-accessible tags into packaging, enabling seamless product data access across the supply chain.

TABLE 5.2: Widely used ICT technologies in food supply chain traceability

This approach, tested in the pork supply chain, facilitates detailed product tracking from farm to consumer, thereby improving safety and quality control. Similarly, WSN and QR codes were combined in SMS-CQ, a system proposed by Xiao et al. [436], designed to guarantee the safety of aquatic products during cold-chain transportation. This solution monitors product conditions in real time, enhancing quality assurance in perishable goods logistics. Li et al. [230] further explored the use of QR codes for food traceability, outlining their technical configurations and comparing them with 1D barcodes and RFID. The study demonstrated QR codes' cost-effectiveness and convenience for digital food data management across the supply chain. Based on the strengths of existing ICT solutions, recent studies have explored the integration of ICT with blockchain in traceability systems to meet the growing demand for transparency, immutability, and consumer trust. Tian [397] proposed a system that combines RFID technology with blockchain to address major food safety scandals in China, such as the Sudan Red and Sanlu toxic milk powder incidents. The system analyzes the advantages and limitations of integrating RFID and blockchain, highlighting their effectiveness in providing secure, end-to-end traceability throughout the supply chain. In another study, Ahamed et al. [15] integrated both RFID and QR code technologies with blockchain to improve traceability in the halal food supply chain. Their system employs specialized tags to trace halal products from farm to table, ensuring product authenticity, reducing contamination risk, and preserving data integrity. FoodSQRBlock [99] is another blockchain-based framework developed to digitize food production data and make it

verifiable through QR codes. This system allows both consumers and producers to access traceability information using mobile or edge devices, supporting real-time data availability across the supply chain. Additionally, another study in [277] proposed a blockchain and QR code-based traceability system aimed at improving transparency, efficiency, and reliability across all stages of the food supply chain. By enabling stakeholders to securely track food products from origin to destination, this approach enhances trust and accountability within the system.

Despite the progress made in previous systems, several limitations remain, particularly in consumer interactivity, the clarity of tracking queries, and the efficiency of query processing in blockchain environments.

5.3 Proposed Model

This section presents a high-level overview of our system with its overall architecture, and explains the design details of its components along with the optimized traceability query scheme.

5.3.1 System Architecture

The proposed system is based on several essential components, including blockchain technology, a B+ tree index, and an NLP model, all carefully designed according to our specifications and integrated to form a robust architecture that addresses the limitations of traditional blockchain-based traceability systems in terms of query performance, and supports efficient traceability searches in the food supply chain process. The general architecture and all system components is illustrated in Figure 5.1.

The core components of our architecture is:

- **Permissioned Blockchain Network:** Implemented to provide secure, decentralized, and tamper-resistant storage of traceability data collected from the food supply chain stages where each block in the network store multiple transactions and each transaction recording structured information such as product ID, supply chain stage, and other traceability details.
- **Smart Contract Component:** Integrated within the blockchain to define and enforce business logic, managing access control so that only authorized supply chain actors can insert, update, or query traceability records.
- **NLP Model:** An NLP model is integrated into the system to interpret user queries. It identifies the specific supply chain stage the user is interested in and helps retrieve the corresponding traceability data.
- **B+ tree Index:** This index is stored in the latest block of the blockchain. It is continuously updated with each new block and allows for fast identification and access to relevant traceability records.

Our system with its components functions to enhance traceability search by efficiently retrieving relevant blocks from the ledger, followed by an intra-block search based on the product ID to obtain the traceability data for the consumer. For example, a traceability query in the distribution stage for product 'ID101' returns transaction data related to this product from

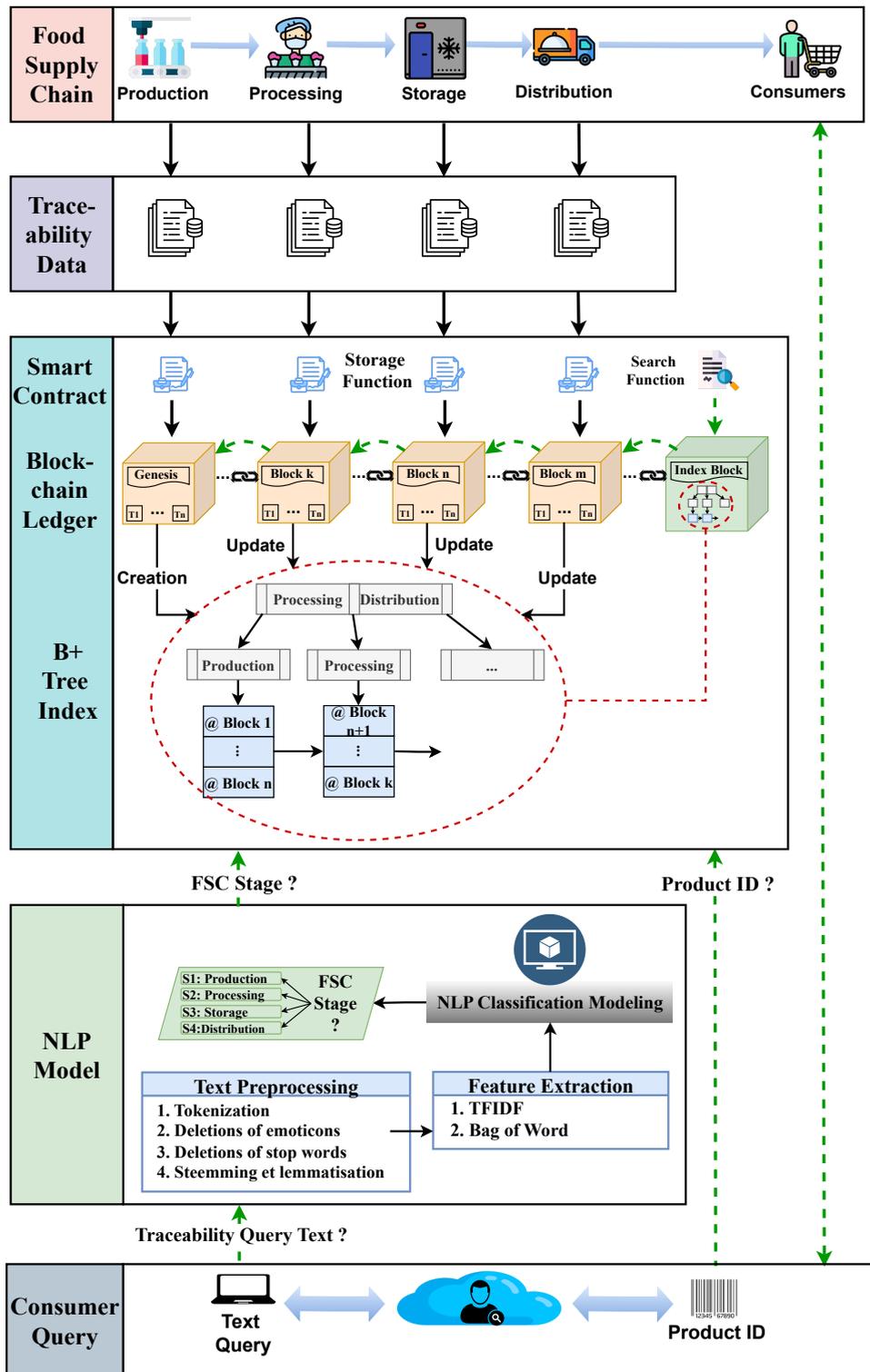


FIGURE 5.1: General architecture of our system

blocks B050 to B075. Within each of these blocks, an intra-block search is performed, scanning all transactions and filtering them based on the specified Product ID. As in block B075, one transaction matching Product ID101 is returned out of five transactions, containing the following traceability information: transaction timestamp (2025-04-15T20:32:56.14Z UTC), product name (Organic Almond Butter), supply chain stage (Distribution), distribution window (2025-04-14 to 2025-04-16), previous node (Processing Facility, California), next node (Regional Distribution Center), current GPS coordinates (39.5153° N, 119.8211° W), transportation mode (certified refrigerated trailer), temperature log (2.8°C ± 0.2°C, recorded every 15 minutes), humidity (45% RH, range 40–50%), cold chain integrity (maintained, average of 3.2°C), and shock events (0, threshold <2.5G).

5.3.2 Blockchain Technology Design

The integration of blockchain technology into the food supply chain creates a traceability solution that incorporates advanced features to improve performance and reliability. By implementing a specially designed blockchain network through the Hyperledger Fabric framework, the system ensures that all information related to food products within the supply chain is securely recorded, verifiable in the blocks, and easily queryable.

1. **Block and Data Structure Design:** In the context of the food supply chain, where the blockchain ledger consists of numerous blocks, each containing multiple transactions related to various food products, we incorporate modifications to the data structure to ensure that historical data about food products are recorded and retrieved efficiently. Our proposed model uses QR codes as unique identifiers for food products in all data transactions within the blockchain network. Additionally, the transaction structure is modified by adding a new attribute to each transaction that specifies the supply chain stage (e.g., production, processing, distribution, retail). With this modification, all transactions within the blocks are assigned both the QR code of the corresponding product and the supply chain stage to which they belong. Furthermore, the block headers in our network now include the supply chain stage of data transactions as a new metadata field, simplifying the identification and retrieval of blocks based on this attribute. This modification improves search efficiency and traceability within the blockchain network by enabling more targeted and specific queries. Figure 5.2 illustrates all the modifications made to the data structure and block headers in our blockchain network.
2. **Smart Contract Design:** The smart contract in our blockchain-based system plays a crucial role in managing traceability data throughout the food supply chain. Its design is based on various functions implemented in the Chaincode, focusing on efficient data generation and querying. The storage function is primarily responsible for ensuring that all informational data within the supply chain process, as well as transaction data exchanged between participants, is added to the blockchain while maintaining integrity and security. The data collected are processed and formatted into a transaction structure suitable for blockchain storage, with each transaction securely recorded as a new entry on the blockchain. This function is implemented as part of the smart contract logic, which runs autonomously whenever a new transaction is initiated, ensuring consistent and automated data handling. Cryptographic techniques such as SHA256 in Merkle trees secure the transaction data, with each transaction being hashed until the final Merkle root hash is generated and included in the block header, ensuring both data integrity and authenticity [220, 425]. Using the storage function, our blockchain-based system provides a robust

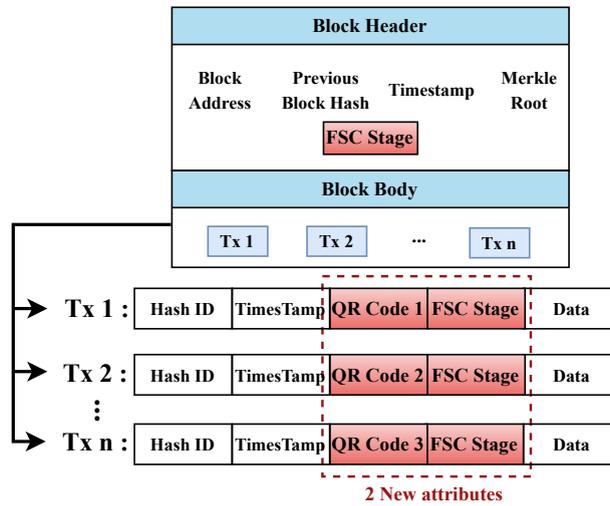


FIGURE 5.2: Structure of data transactions and block headers in our system

solution to maintain the traceability of food products while securely recording all data changes throughout the supply chain process. The query function is another critical component of our traceability system, implemented as part of the smart contract logic. It is designed to execute autonomously for consumers, retrieving traceability data from the blockchain ledger for specific food products, including their journey through various supply chain stages such as production, processing, distribution, and retail. By incorporating the B+ tree index into the traceability query process, this function enhances the speed and accuracy of data retrieval while restricting queries to relevant blocks, thereby eliminating unnecessary data processing.

5.3.3 B+ Tree Index Design

Following the design of our blockchain network for the food supply chain, we implement the B+ tree index within a specific block located in the most recent block (latest) of the network. This index is created simultaneously with the blockchain network and efficiently manages the addresses of blocks and supply chain stages, enabling quick retrieval of traceability data from a vast number of blocks. The general process of designing the B+ tree in our blockchain network is illustrated in Figure 5.3.

Our approach utilizes an indexing method based on the B+ tree structure, a self-balancing tree that maintains sorted data and enables efficient insertion and search operations. It is an extension of the B-tree structure, where all values are stored at the same depth at the leaf level to ensure optimal access time, while internal nodes store only keys to guide the search process. The complexity of B+ tree operations, such as insertions and searches, is $O(\log n)$, making it highly efficient for managing large datasets by minimizing the number of disk reads [126, 200]. In our blockchain-based system, the two processes of constructing and updating the B+ tree index are essential for establishing the final version of the index, synchronized with the ledger. These processes enhance accuracy and ensure the efficiency of the traceability query process.

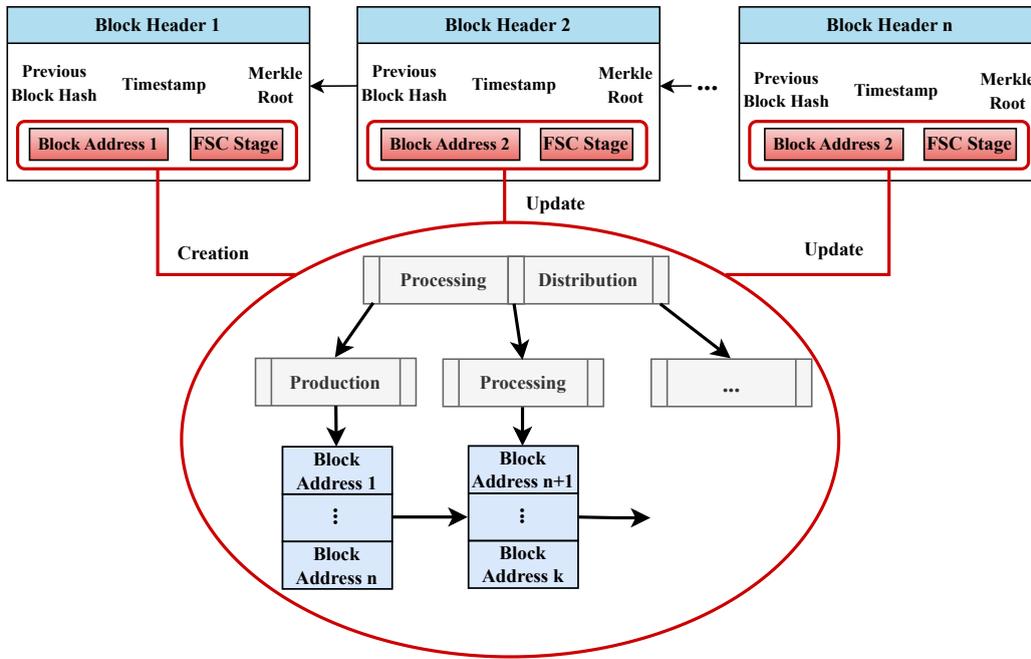


FIGURE 5.3: B+ tree index design in the blockchain network

Construction and Update of B+ Tree Index

The construction and update of the B+ tree involves creating nodes and organizing data into a hierarchical structure that facilitates rapid insertion and searching. Specifically, when new blocks are added to the blockchain with specific data transactions, the supply chain stage and the corresponding block address are dynamically inserted into the B+ tree, which the stage serves as the key, and the block address serves as its value. By using food supply chain stages as keys in the B+ tree index, we can logically partition the blockchain ledger into sub-ranges of blocks corresponding to each supply chain stage, effectively reducing the inter-block search space. In contrast, using other types of keys, such as Product ID, prevents a clear division of the ledger into distinct block ranges, as each block typically contains multiple transactions with different Product IDs, and thus does not reduce the inter-block search space.

Algorithms 5.1 and 5.2 define the complete process of constructing and updating the B+ tree index in our system.

Algorithm 5.1 begins by checking if the B+ tree is empty (Line 1). If it is, a root node is created with the first key-value pair, where the key is the FSC Stage (e.g., "Production") and the value is the Block Address (e.g., the address of the genesis block) (Line 2). If the tree is not empty, the algorithm calls the `InsertIntoBPlusTree` function to insert the new key-value pair into the tree, starting from the root node (Line 4).

The `InsertIntoBPlusTree` function (Line 6) first checks if the current node is a leaf node (Line 7). If it is a leaf node and has space, the new key-value pair is inserted in sorted order (Line 9). If the leaf node is full, it is split into two nodes (Line 11), and the new key-value pair is inserted into the appropriate node (left or right) based on its value (Lines 12–15). The parent node is then updated to reflect the new split nodes (Line 17). If the current node is not a leaf node, the algorithm identifies the appropriate child node for insertion based on the sorted order of keys

Algorithm 5.1 B+ tree index construction**Require:** FSC_Stage, Block_Address**Ensure:** B+ tree index

```

1: if B+ tree is empty then
2:   Create RootNode (FSC_Stage, Block_Address)
3: else
4:   InsertIntoBPlusTree(RootNode, FSC_Stage, Block_Address)
5: end if
6: function INSERTINTOBPLUSTREE(Node, New_FSC_Stage, Block_Address)
7:   if Node is a leaf node then
8:     if Node is not full then
9:       Insert (New_FSC_Stage, Block_Address) into Node in sorted order
10:    else
11:      Split Node into two nodes
12:      if New_FSC_Stage is less than the first key in the right node then
13:        Insert (New_FSC_Stage, Block_Address) into the left node
14:      else
15:        Insert (New_FSC_Stage, Block_Address) into the right node
16:      end if
17:      Update the parent node with the new split nodes
18:    end if
19:  else
20:    Find the child node where New_FSC_Stage belongs
21:    InsertIntoBPlusTree(ChildNode, New_FSC_Stage, Block_Address)
22:  end if
23: end function

```

Algorithm 5.2 B+ tree index update**Require:** FSC_Stage, Block_Address**Ensure:** Updated B+ tree Index

```

1: if FSC_Stage already exists in the B+ tree then
2:   Update existing key with new Block_Address as value
3: else
4:   InsertIntoBPlusTree(Root_Node, FSC_Stage, Block_Address)
5: end if

```

(Line 20) and recursively calls the InsertIntoBPlusTree function to insert the new key-value pair into the correct child node (Line 21).

Furthermore, Algorithm 5.2 ensures that the B+ tree index is updated with the latest key-value pairs (FSC Stage and Block Address) from the blockchain ledger. This allows the index to remain dynamic, ensuring real-time synchronization with the blockchain ledger and enabling efficient data retrieval.

5.3.4 NLP Model Design

The NLP model in our system plays a crucial role in optimizing the search query process. Its primary objective is to accurately interpret consumer text queries about food products and extract the target stage of the supply chain required by the query. By converting natural language

queries into precise search parameters and classification outputs, this NLP model ensures that only the relevant blocks of the target stage containing the desired traceability data are queried, rather than all blocks across all stages. This approach significantly enhances search efficiency and reduces the computational resources needed to retrieve traceability information.

Furthermore, we integrated the NLP model into our traceability system due to its superior performance in extracting detailed information from text queries compared to traditional techniques like QR codes and barcodes. While these techniques provide a unique identifier for a product, they lack the ability to capture and interpret the nuanced details that natural language queries can offer. The NLP model can understand complex queries and extract relevant details that might be missed by simpler identification techniques. This leads to a more comprehensive and accurate traceability system, providing users with detailed and contextually rich information about the food products in question (see Table 5.3).

Feature (Functional/Technical)	Traditional ICT Tools (QR, RFID)	NLP-Based Models
Interaction Mode	One-way (scan to retrieve data)	Two-way (natural language dialogue)
Query Type Supported	Simple key-based queries (e.g., product ID)	Complex and contextual queries (e.g., dietary needs, origin, conditions)
Data Flexibility	Static and limited data	Dynamic and adaptable data access
User Personalization	No personalization; same output for all users	Personalized answers based on user intent or preferences
Ease of Use	Requires scanning devices/apps	Intuitive input through natural language
Interaction Tools	Physical tags, scanners, mobile apps	Chatbots, voice assistants, web interfaces
Data Transparency	Limited to pre-encoded fields	Full access to detailed and relevant data
Response Adaptability	Fixed data, same format	Context-aware, flexible responses
Query Depth	Superficial (basic attributes only)	Deep (specific steps, context-aware)
Scalability	Limited by tag memory and format	Highly scalable with backend data systems

TABLE 5.3: Consumer query technologies: Traditional ICT tools vs. NLP-based models

The development of our NLP model involves several key steps to ensure accurate and efficient processing of natural language queries including: text preprocessing, feature extraction, and classification (see Figure 5.4).

1. **Text Preprocessing:** This step involves cleaning and normalizing the input text to remove noise and standardize the data for further processing. Techniques such as tokenization, stop-word removal, and stemming or lemmatization are used to prepare the text

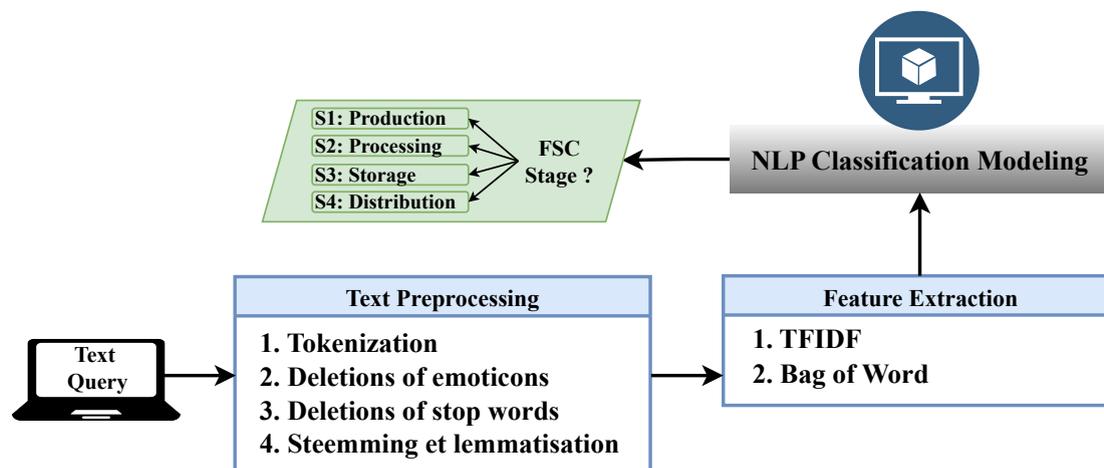


FIGURE 5.4: NLP model design [294]

data [412].

2. **Feature Extraction:** In this step, relevant features are extracted from the preprocessed text by converting the text into numerical representations that can be used by machine learning algorithms. Common methods include Term Frequency-Inverse Document Frequency (TF-IDF) [348], Word Embeddings (WE), and Bag of Word (BW) [147].
3. **Classification Modeling:** The core of the NLP model, this step involves training a classification algorithm to categorize the processed text into one of the predefined supply chain stages. Various machine learning models such as Support Vector Machines (SVM), Random Forests (RF), or neural networks can be used for this purpose [223].
4. **Classification Results:** The final step uses the trained model to classify new text queries. The output is the supply chain stage (e.g., production, processing, distribution, retail) that corresponds to the query.

By incorporating these steps, the NLP model provides a sufficient mechanism to handle natural language queries, thereby enhancing the efficiency and accuracy of our traceability system within the food supply chain. It introduces a novel technique that allows consumers to write text queries about the traceability of food products, and the model extracts the relevant stage of the supply chain from the text. This improves the performance of the search query, making it more efficient compared to traditional methods that consult all blocks of the supply chain during the query process.

5.3.5 Traceability Query Design

The traceability query process in our system is designed to efficiently retrieve historical data about food products from the blockchain ledger, thereby optimizing searches within the food supply chain. This process involves two complementary types of queries, each working at a different level and using a different key. The inter-block query operates at the blocks level, where indexing is based on the food supply chain stage as the key, because it is a shared attribute across all transactions within a block and it is efficient to group and locate relevant blocks in the ledger. This significantly accelerates the initial phase of the traceability query by

identifying the appropriate block ranges. The intra-block query, which forms the second part of the process, operates at the transactions level using the Product ID as the key, as it uniquely identifies a specific food item and enables precise filtering of relevant transactions within the selected blocks. The complete traceability query process, from the consumer query to retrieving traceability data, is presented in the sequence diagram in Figure 5.5, illustrating all interactions among system components and details both the inter-block and intra-block query steps.

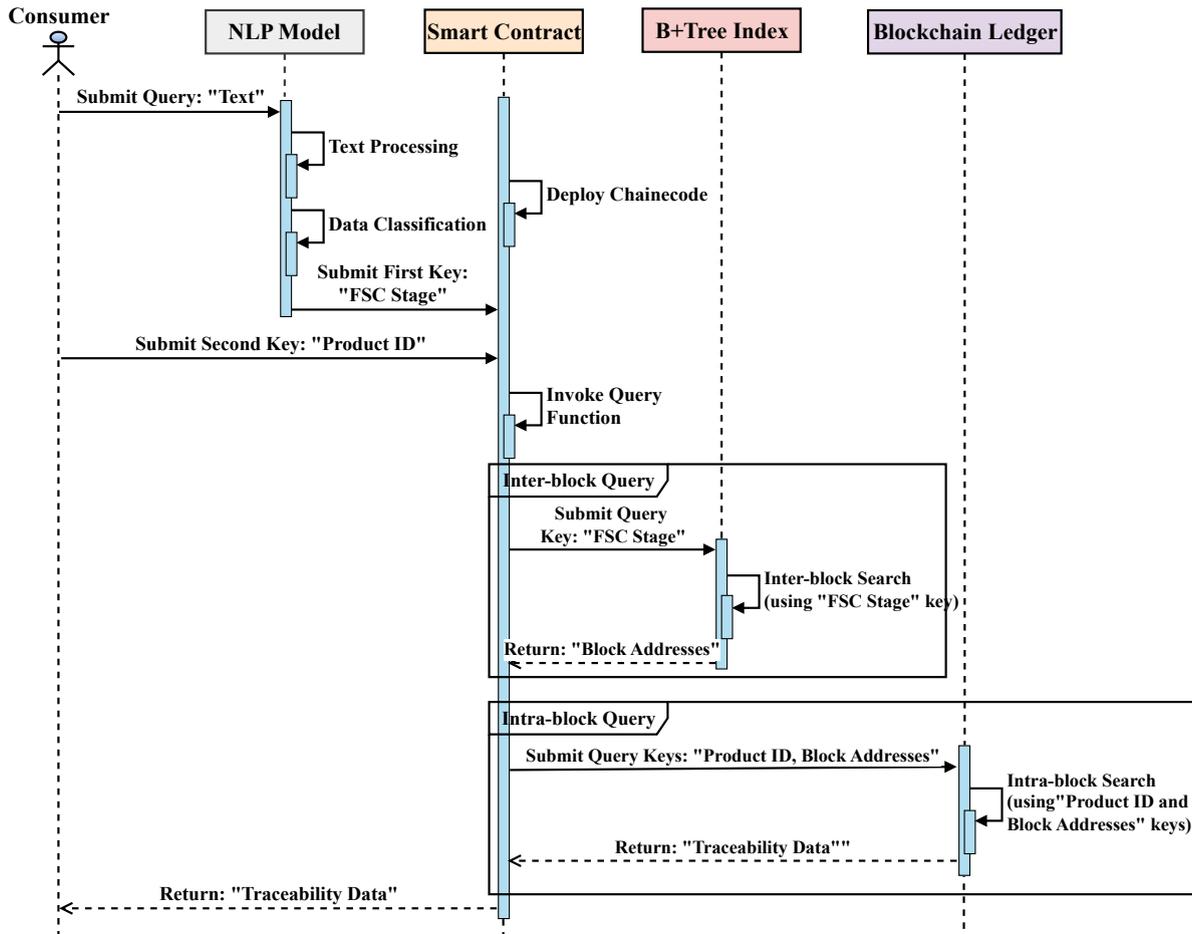


FIGURE 5.5: Sequence diagram for traceability query process in our system

1. **Traceability Query in B+ tree Index:** The first part of the traceability query process involves querying the B+ tree index, located in the last block of the blockchain ledger. When a query is initiated by the consumer, the NLP model processes the consumer's natural language query to extract the target supply chain stage, which is then used as the query key in the B+ tree index. Leveraging its logarithmic search performance, the B+ tree index efficiently locates and returns the addresses of blocks containing data for the specified supply chain stage. This initial part of the query significantly reduces the number of blocks requiring further examination, thereby optimizing query performance. The query process in the B+ tree index is detailed in Algorithm 5.3.
2. **Traceability Query in Blockchain:** Once the relevant block addresses are obtained from the B+ tree index, the second stage of the query process involves querying these target blocks. The system accesses the blocks identified by the index to retrieve traceability data specific to the food product. This intra-block query uses the QR code as identifier of

Algorithm 5.3 Traceability query in B+ tree index**Require:** Text_Query, BPlusTree_Index (Root Node)**Ensure:** Relevant_Block_Addresses

```

1: FSC_Stage_Key ← NLP_Model(Text_Query) ▷ Extract target supply chain stage using
   NLP model
2: Relevant_Block_Addresses ← Query_BPlusTree(BPlusTree_Index, FSC_Stage_Key)
3: function QUERY_BPLUSTREE(Node, FSC_Stage_Key)
4:   if Node is a leaf node then
5:     Block_Addresses ← Retrieve_Block_Addresses(Node, FSC_Stage_Key) ▷ Get
     addresses associated with Stage_Key
6:     return Block_Addresses
7:   else ▷ Node is an internal node
8:     ChildNode ← Find_Child_Node(Node, FSC_Stage_Key) ▷ Locate child node
     where Stage_Key belongs
9:     return Query_BPlusTree(ChildNode, FSC_Stage_Key)
10:  end if
11: end function
12: return Relevant_Block_Addresses

```

the food products to locate the target data within the transactions of each relevant block, which may contain numerous transactions related to various food products. The query is executed through a function in the smart contract code, with the block addresses and the QR code of the product as input arguments. This function retrieves and presents traceability data, providing detailed information about the products progression through different supply chain stages to consumers. By focusing exclusively on target blocks, the system ensures an efficient and accurate query process, delivering precise and relevant traceability information. The query process in the blockchain ledger is detailed in Algorithm 5.4

These two parts form the traceability query process of our system, significantly improving efficiency and optimizing historical data searches in the food supply chain, outperforming traditional methods that require scanning all blocks within the blockchain network.

5.4 Experiments

In this section, we present a series of rigorous experiments designed to evaluate the efficiency of the query process, the accuracy of data retrieval, and the overall robustness of the system in handling real-world supply chain scenarios. By comparing our approach with traditional methods, we demonstrate how the NLP model and B+ tree index enhances query performance while ensuring high accuracy and efficiency in managing traceability data. This section details the experimental setup, datasets, results, and an in-depth analysis of the findings.

5.4.1 Settings

Our proposed system was implemented using the Hyperledger Fabric framework due to its simplicity, clarity, and suitability for the food supply chain domain, considering the architectural

Algorithm 5.4 Traceability query in blockchain ledger**Require:** Relevant_Blocks, QR_Code**Ensure:** Traceability_Data

```

1: Traceability_Data ← Empty_List
2: for each Block_Address in Relevant_Blocks do
3:   Block ← Access_Block(Block_Address)           ▷ Access the block using its address
4:   Product_Data ← Query_Block(Block, QR_Code)    ▷ Query the block for data related
   to the QR_Code
5:   if Product_Data is not empty then
6:     Append Product_Data to Traceability_Data ▷ Add the product data to the results
7:   end if
8: end for
9: return Traceability_Data                       ▷ Return the collected traceability data to the consumer
10: function QUERY_BLOCK(Block, QR_Code)
11:   for each Transaction in Block do
12:     if Transaction.QR_Code = QR_Code then
13:       return Transaction.Traceability_Info    ▷ Return the traceability info associated
   with the QR_Code
14:     end if
15:   end for
16:   return Empty                               ▷ Return empty if no matching QR_Code is found
17: end function

```

and functional differences among blockchain frameworks [32]. Before initializing the test network, several parameter configurations were necessary, with particular attention given to the consensus mechanism and the smart contract. We chose the Raft consensus algorithm for its reliability and flexibility within the network. Additionally, we customized the smart contract (Chaincode.go) to meet our specific requirements. The smart contract functions were designed to build and query the blockchain ledger using SDK tools, such as CLI commands. Notably, we used the GetKeyHistory function to extract historical data of specific food products from the blockchain ledger, which served as a baseline for comparison with our optimized method (see Table 5.4).

To thoroughly evaluate our solution, we considered two scenarios under various parameters that impact query performance. The key parameters are defined as follows:

1. **Blockchain Size:** This parameter represents the total number of blocks in the blockchain network, which is influenced by the complexity of the supply chain and the volume of data, and it significantly affects query performance. For our experiments, we varied the values of this parameter while fixing the maximum capacity of each block at 99 MB.
2. **Data Size:** This refers to the number of transactions stored in each block, which can be set in the simulator configuration file (Configtx) using the parameter (MaxMessageCount). Additionally, the maximum size of each individual transaction was set to 3.5 MB.
3. **Target Blocks Size:** This parameter represents the number of blocks relevant to a specific query based on the supply chain stage. It is defined as one-fourth of the total blockchain size.
4. **Target Data per Block Size:** This factor denotes the amount of traceability data pertinent to the query in each target block, significantly influencing the query search time.

Component		Description
Blockchain Framework		Hyperledger Fabric (v2.x): A permissioned blockchain framework suited for supply chain applications due to its modularity and support for private data.
Consensus Mechanism		Raft: Chosen for its crash fault tolerance and simplicity in maintaining leader-based consensus.
Smart Contract		Chaincode.go: Customized Go-based chaincode implementing business logic for storing and querying traceability data.
SDK Tools		CLI Commands: Used to interact with the network, deploy chaincode, and call functions like <code>GetKeyHistory</code> .
Programming Language		Go (Golang): Used to develop chaincode due to its compatibility with Hyperledger Fabric.
Development Environment		Linux Mint: Used along with Docker and Docker Compose to configure and deploy the network.

TABLE 5.4: Materials used in the implementation

Table 5.5 provides an overview of the scenarios employed in our experimental tests with multiple parameter configurations.

	Blockchain Size	Data Size	Target Blocks Size ($1/4 \times$ Blockchain Size)	Size of Target Data per Block
Scenario 1	1000, 2000, 3000, 4000, 5000	5 transactions	250, 500, 750, 1000, 1250	1 transaction
Scenario 2	1000, 2000, 3000, 4000, 5000	20 transactions	250, 500, 750, 1000, 1250	1 transaction

TABLE 5.5: Simulation scenarios and data configuration

For our experiments, we disabled the state and history databases and removed the indexing methods for key-value pairs in the Hyperledger Fabric. This configuration allowed us to conduct direct timing measurements of querying historical transactions from the ledger. Additionally, through a series of tests, we analyzed how variations in blockchain size, data size, and other key factors influenced the effectiveness and responsiveness of our system. The following analysis provides insight into our findings and their relevance in enhancing data traceability within blockchain technology.

5.4.2 Results and Analysis

We present the experimental results and analyze the performance of our blockchain-based traceability system by showing the findings of our NLP classification model and examining query performance in the B+ tree index and the blockchain ledger across the two scenarios.

NLP classification model performance

To evaluate the performance of our NLP model in classifying consumer queries into their respective food supply chain stages, we conducted experiments using a dataset collected from 54 consumers, comprising of 270 labeled traceability queries. The dataset was cleaned, preprocessed, and then split into training and testing sets using a standard 80/20 ratio, resulting in 54 queries for testing. The classification model was based on a TF-IDF vectorizer combined with SVM classifier. The performance of our model on the test set is represented by the confusion matrix in Figure 5.6 and the classification report in Figure 5.7.

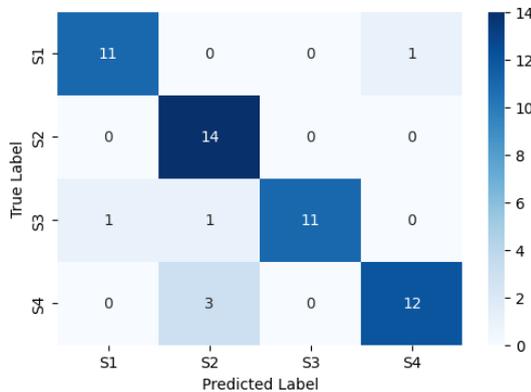


FIGURE 5.6: Confusion matrix of our model on the test set

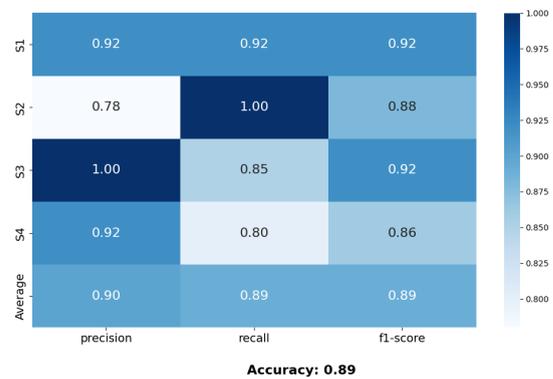


FIGURE 5.7: Performance report of our classification model

The classification results demonstrate that the model achieves an overall accuracy of 89%, along with strong precision, recall, and F1-score of 90%, 89%, and 89%, respectively, indicating solid performance across all food supply chain stage categories. The high precision and recall values for most classes suggest that the model is effective in handling the classification task, despite the limited size of the dataset. However, it is important to note that this model serves as a lightweight and sufficient solution to demonstrate the feasibility of using NLP to guide inter-block queries in the blockchain-based traceability system, and further evaluation on larger datasets would be necessary to confirm its robustness.

B+tree Index Performance

The evaluation of the B+ tree index focuses on insertion and search operations, highlighting its capability to manage large-scale traceability data within the food supply chain system. Specifically, we analyze the time required to insert block addresses as values with their corresponding supply chain stages as keys across different blockchain sizes. We also calculate the time required to look up a single key (e.g., key='Production'), which corresponds to a quarter of the blockchain size, as shown in Figure 5.8.

By efficiently identifying relevant addresses associated with a specific supply chain stage, the B+ tree index optimizes the query process, reducing the search space within the blockchain ledger. The performance results of B+ tree are presented in Figure 5.9, which provides a detailed comparison of insertion and search times. The left chart in the figure illustrates the insertion times, while the right chart highlights query times for retrieving data related to a single stage.

The results demonstrate the efficiency and scalability of the B+ tree index. The left chart shows that insertion time increases linearly with blockchain size, as more addresses and keys are added

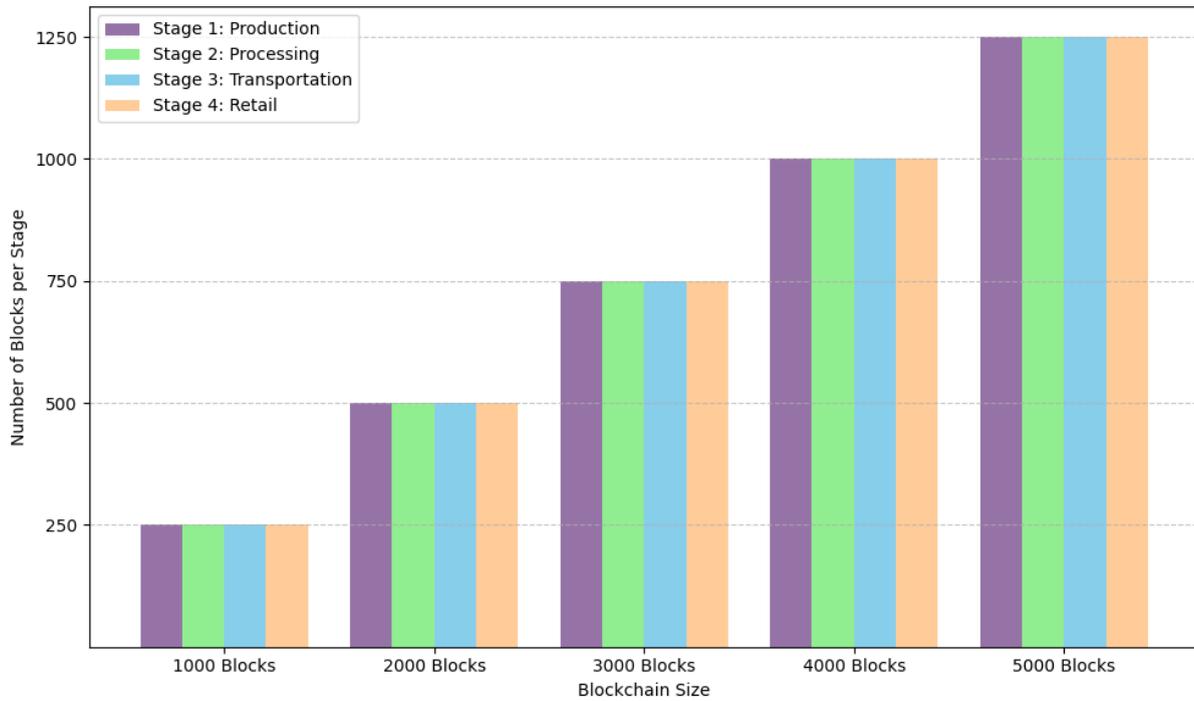


FIGURE 5.8: Block distribution across supply chain stages for different blockchain sizes

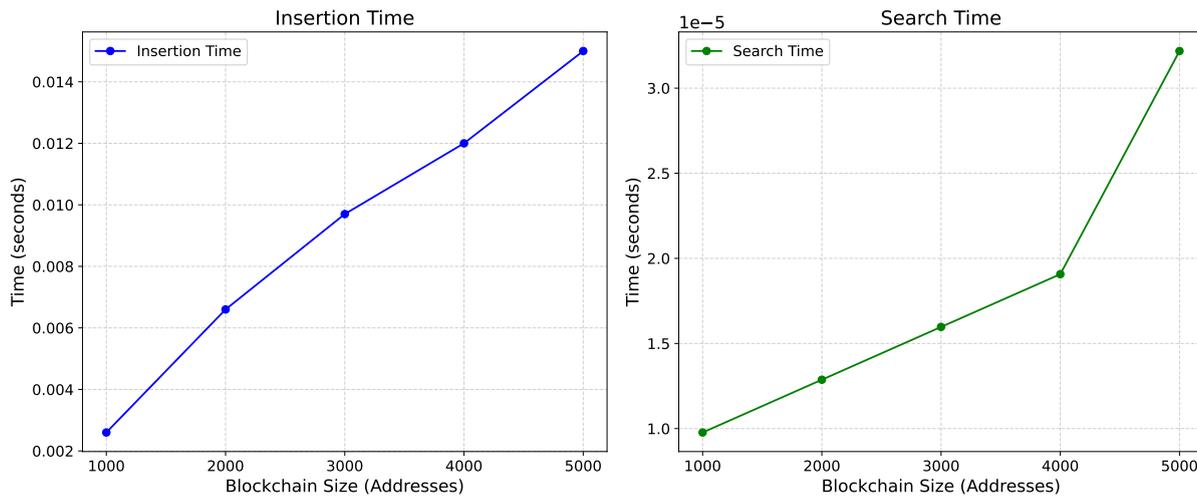


FIGURE 5.9: Performance of the B+ tree index across blockchain sizes: Insertion and Search times

to the index. For example, for a blockchain size of 1000 addresses, the insertion time is 0.0026 seconds, while for the largest size (5000 addresses), the time remains below 0.016 seconds. This behavior is expected due to the structured and efficient nature of the B+ tree, which organizes data hierarchically to maintain balance during insertions.

From the right chart, it is evident that search times remain consistently low, even with significant increases in blockchain size. For instance, the query time for 1000 addresses is approximately 9.77 microseconds, increasing only slightly to 32 microseconds for 5000 addresses. This minimal growth in query time, despite the expanding blockchain, highlights the robust performance of the B+ tree index and its logarithmic search efficiency.

The structure of the B+ tree enables rapid insertion and retrieval of block addresses, efficiently managing the block addresses and significantly enhancing search efficiency of traceability data.

Traceability Query Performance

After analyzing the performance of the B+ tree index, we evaluate the traceability query process within the blockchain ledger. The traditional approach involves scanning the entire blockchain to locate relevant data without using any indexing techniques. In contrast, our method leverages the B+ tree index, which has shown remarkable efficiency, as illustrated in Figure 5.9. To provide a comprehensive performance evaluation, we conducted experiments under the two scenarios defined in Table 5.5 and tested the query process using both methods in the blockchain simulator.

In the first scenario, the evaluation is conducted under conditions where the data size is fixed at 5 transactions per block across various blockchain sizes. The distribution of data transaction, in terms of target transactions and total transactions, is detailed in Figure 5.10, indicating that the size of target transactions constitutes 5% of the total size in all blockchain sizes. This demonstrates the efficiency of our query and provides a reliable measure of performance. Figure 5.11 illustrates the performance comparison of traceability queries within the blockchain ledger for both the traditional method and our proposed method.

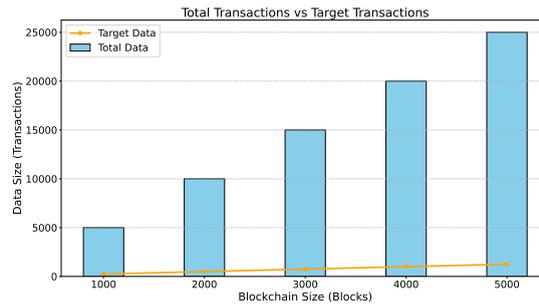


FIGURE 5.10: Data distribution of the first scenario

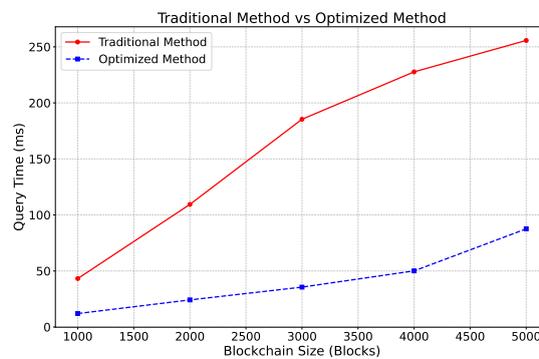


FIGURE 5.11: Query performance of the first scenario

In Figure 5.11, the traditional method shows a noticeable decrease in performance, with query times ranging from 43.24 ms for 1000 blocks (250 target transactions) to 255.72 ms for 5000 blocks (1250 target transactions). This demonstrates the inefficiency and scalability challenges of the traditional approach in handling larger blockchain sizes with large data transactions. In contrast, the optimized method, which leverages the B+ tree index, significantly outperforms the traditional method. Query performance for the optimized method ranges from 12 ms to 87.59

ms as the blockchain size grows. This remarkable improvement is attributed to the efficiency of the B+ tree index, which minimizes search space and maintains lower query times even as the blockchain size expands.

In the second scenario, the number of transactions per block is increased to 20, which also leads to an overall increase in total transaction size, but the target blockchain size remains one-fourth of the total blockchain size, with the same number of target data transactions. Figure 5.12 illustrates the data transaction distribution for this scenario, while Figure 5.13 presents the experimental results, highlighting query performance across various sizes of the blockchain.

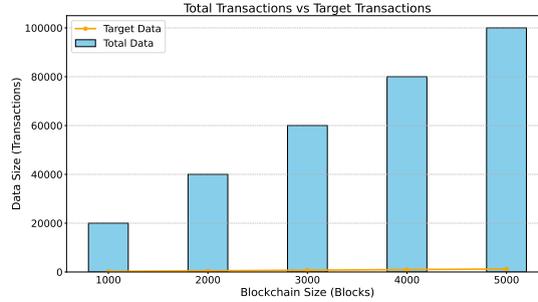


FIGURE 5.12: Data distribution of the second scenario

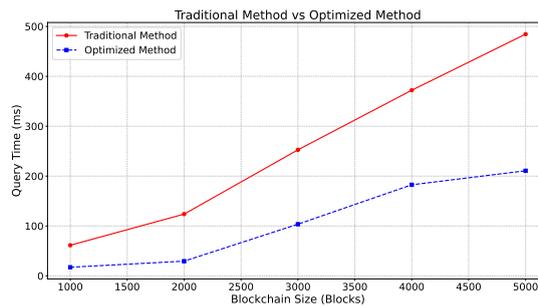


FIGURE 5.13: Query performance of the second scenario

Figure 5.13 shows that the results for both methods are higher than in the previous scenario, primarily due to the increase in transaction data size. However, the optimized method still demonstrates more stable query performance compared to the traditional method across all blockchain sizes. Query times for the optimized method range between 17.27 ms and 210.69 ms, whereas the traditional method exceeds 61 ms in the initial case and rises to 484.53 ms in the largest case. Although the increase in blockchain size and transaction data can influence query search times, it has minimal impact on the performance of our method based on the B+ tree index.

Furthermore, based on the results in Figures 5.11 and 5.13, we observed an impact on the performance of traceability queries in each method, depending on the size of transaction data in the network. Specifically, with 20 transactions per block, the performance of each method is significantly worse compared to 5 transactions per block, even though the target blocks and target transaction data are the same. This demonstrates a time overhead in intra-block queries performed within the blocks of the network. To address this, we compared traditional and optimized methods, examining how the size of transaction data per block affects query performance. Figure 5.14 shows the performance difference between the two cases (5 and 20 transactions per block) for both methods.

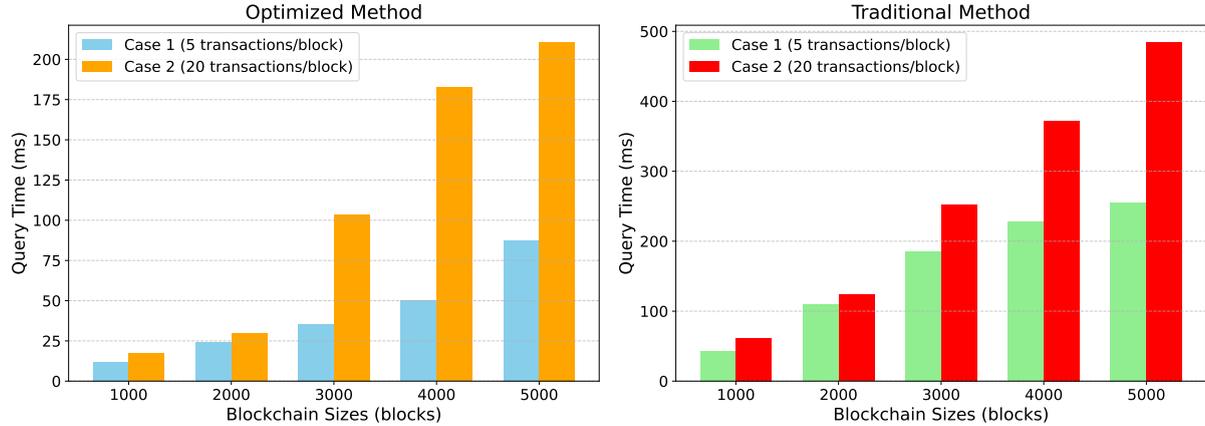


FIGURE 5.14: Intra-block query time overhead based on transaction data size: Traditional vs. Optimized method

In Figure 5.14, the query performance of the two methods shows a noticeable difference between the two cases (5 and 20 transactions per block). For the optimized method, with a blockchain size of 1000 blocks, the query time for Case 1 is 12 ms, while Case 2 requires 17.27 ms—an increase of approximately 5 ms. However, as the blockchain size and the number of transactions increase, this difference becomes more significant, rising from 87.59 ms to 210.69 ms at 5000 blocks, resulting in a gap of 123 ms. In the traditional method, the performance difference is even more substantial. For a blockchain size of 1000 blocks, the query time for Case 1 is 43.24 ms, whereas Case 2 takes 61.42 ms—a difference of 18 ms. This difference grows significantly at 5000 blocks, increasing from 255.72 ms to 484.53 ms, resulting in a large gap of 228 ms. This gap in both methods expands significantly with the growth of both blockchain size and transaction volume, emphasizing the time overhead of intra-block query.

5.4.3 Discussion

The optimized method, based on the NLP model and B+ tree index, achieves significant improvements in query performance across the two scenarios illustrated in Figures 5.11 and 5.13. The experimental results demonstrate that blockchain size and data transaction volume significantly influence search time, with the optimized approach delivering 4 to 5 times faster query performance compared to the traditional method.

In traditional methods, query time increases proportionally as the number of blocks in the ledger and the size of target blocks containing relevant data grow. In contrast, the optimized method shows only a slight increase in query time across all scenarios. This method divides the query time into two parts: the time spent in the B+ tree index and the time spent in the blockchain ledger. The B+ tree index plays a critical role in minimizing time overhead within the blockchain ledger by efficiently managing a large number of block addresses, thereby significantly enhancing query performance, particularly for specific queries. In addition, to support our performance, the smart contracts (chainecode) were carefully developed to ensure that all interactions with the ledger were secure, verifiable, and correctly executed. The query functions in these contracts enabled read operations to be properly performed in the blockchain ledger based on identified block addresses and Product ID as query arguments and allowed response times to be recorded during query execution. This selective query logic facilitating a thorough evaluation of system performance in terms of latency and scalability under various network and data configurations,

thus demonstrating how smart contract design directly contributes to optimized data retrieval from the blockchain.

We compared our system with two distinct categories of systems: food supply chain systems leveraging blockchain and ICT technologies, focusing on data integrity and acquisition, and blockchain-based traceability systems, specifically evaluating optimization of traceability queries. The first comparison was conducted based on several key features, including the technology employed, identification methods, contributions to food safety, real-time data acquisition capabilities, scalability, and cost. The second comparison focused on traceability query optimization, considering criteria such as the blockchain platform, query types, index structures, factors influencing query performance, query complexity, and storage overhead. The results of these comparisons, which highlight the advantages and superior performance of our system, are summarized in Tables 5.6 and 5.7.

In general, our approach enhances data integrity and real-time acquisition while maintaining scalability and cost-efficiency. Furthermore, when evaluated against other blockchain-based traceability systems, our method improves traceability queries by reducing the number of blocks scanned, resulting in faster and more accurate search results.

5.5 Conclusion

This chapter examines the effectiveness of an NLP model to replace the direct ICT technologies emphasizing the limitations of traceability queries in terms of accuracy and time performance to maintain food safety and quality standards for consumers. Through the integration of an NLP model and an indexing technique with blockchain technology, we present a novel blockchain-based traceability system aimed at enhancing data retrieval and optimizing the traceability query process within the blockchain ledger. This system outperforms traditional approaches through a two-step process. First, the NLP model identifies the target stage of the supply chain from the text query written by the consumer. Second, the B+ tree index optimizes the search by locating the target blocks corresponding to this stage in the ledger, ensuring that the search query process is performed only within these blocks. The experimental results demonstrate that the proposed system significantly improves the performance of traceability queries, enabling faster and more reliable access to critical information compared to traditional approaches.

Future enhancements could focus on integrating more advanced techniques, such as transformer-based models and large language models (LLMs), including fine-tuning, which have demonstrated superior capabilities in understanding complex natural language inputs and reducing food supply chain stage misclassification rates. Additionally, extracting further information from user queries alongside the food supply chain stage would enable more detailed and multi-criteria traceability searches in the blockchain ledger, thereby improving the precision of the returned traceability data for consumers.

Technology Used	Food Safety Contribution	Data Storage	Identification Method	Real-Time Data Acquisition	Scalability	Cost
[397] RFID and Blockchain	Data Integrity and Traceability	Blockchain	RFID tags	Moderate (depends on RFID infrastructure)	Moderate (depends on RFID infrastructure)	High (RFID tags are costly)
[310] NFC and Blockchain	Transparency and Quality Control	Cloud Database	NFC tags	High (NFC allows real-time interactions)	Limited (NFC infras. required at each stage)	High (NFC tags and readers are costly)
[15] RFID, QR Codes, and Blockchain	Traceability and Monitoring	Blockchain	RFID tags and QR codes	High (RFID and QR allows real-time tracking)	Moderate (RFID and QR requires dual infrastructure)	High (RFID and QR code integration)
[230] QR Codes	Data Integrity	Cloud Database	QR codes	Low (QR codes require manual scanning)	High (wide availability of QR codes)	Low (QR codes inexpensive)
[436] WSN and QR Codes	Monitoring and Quality Control	Blockchain	QR codes	High (WSN and QR allow real-time monitoring)	Moderate (requires WSN devices)	Moderate (cost of WSN deployment)
Ours NLP, QR Codes, B+ tree and Blockchain	Accurate Integrity and Traceability	Blockchain	QR codes	Very High	Very High (efficient data management with B+ tree)	Low (low cost for QR codes)

TABLE 5-6: Comparison of our system with others FSC systems in terms of data integrity and acquisition

Blockchain Platform	Indexing Type	Index Structure	Query Influencing Factors	Query Complexity	Storage Overhead
[178] Hyperledger Fabric	Inter-block & Intra-block	Adaptive Balanced Merkle Tree	Blockchain size, Data vol./block, Network config., Hardware resources	$O(N) \sim (\log N)$	High
[330] Hyperledger Fabric	Inter-block & Intra-block	Deterministic Append-only Skip List	Query complexity, Consensus, Network latency	$O(\log p N)$	Medium
[439] Ethereum	Inter-block & Intra-block	Subchain Index, MHT + B+tree	Blockchain size, Subchains Nb., Query complexity	$O(N)$	Medium
[140] Hyperledger Fabric	Inter-block & Intra-block	MHT + B+Tree, Hash Table	Index structure, Query type, Blockchain size	//	Medium
[218] Hyperledger Fabric	Inter-block & Intra-block	MHT + B+tree, Independent Index	Query complexity, Data volume, Indexing technique	$O(\log N)$	High
Ours	Inter-block & Intra-block	B+ tree index	Blockchain size, Data volume	$O(\log N)$	Low

TABLE 5.7: Comparison of our system with others blockchain-based traceability systems in terms of query optimization

CHAPTER 6

MERKLEB+ TREE FOR INTRA-BLOCK QUERY OPTIMIZATION

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6.1 Introduction and Research Questions

In the previous chapters, we addressed the challenge of traceability query efficiency at the inter-block level by integrating an appropriate indexing mechanism to locate relevant blocks. While this significantly improved query performance across multiple blocks, efficient data retrieval within individual blocks remains a critical concern especially as the number of transactions stored in each block increases. The sequential nature of blockchain, which stores data in an incremental, block-based manner, introduces a temporal constraint, resulting in linear time complexity when retrieving specific transaction data.

This chapter focuses on optimizing intra-block queries, which involve locating and extracting relevant data entries from within a single block. Unlike inter-block queries that navigate across multiple blocks, intra-block queries require a fine-grained mechanism to eliminate sequential scanning of transactions and to efficiently search, filter, and retrieve desired information within the transaction list of a given block. To address this, we propose the integration of a B+ Tree indexing structure with the Merkle tree within each block. This hybrid design aims to enhance search speed, reduce linear scans, and enable low-latency access to traceability data, while preserving the security guarantees offered by the Merkle tree.

The research questions of this contribution are formulated based on the goal of enhancing traceability queries in the food supply chain using blockchain technology, with a specific focus on optimizing intra-query processing (see Table 6.1).

RQs	Research Question	Key Improvement
RQ1	How can the process of querying related transactions in a large-scale blockchain ledger be improved?	Improve intra-block query performance by integrating indexing mechanisms to reduce transaction scanning overhead.
RQ2	What is the most suitable indexing structure for supporting intra-block and range-based queries in combination with Merkle trees in blockchain-based food supply chain systems?	Evaluate B+ tree indexing as a complement to Merkle trees for supporting efficient intra-block range queries.

TABLE 6.1: Research questions and key improvements

6.2 Related Works

Optimizing intra-block queries is a critical aspect of enhancing the responsiveness and scalability of blockchain tracking systems, especially when dealing with large volumes of transaction data within blocks. Unlike inter-block queries, which rely on traversing block metadata, intra-block queries require efficient access to transaction data within individual blocks. Several studies have proposed structural modifications or indexing mechanisms to support more efficient execution of intra-block queries.

The first significant work [178] introduces a new storage layer in the blockchain called Adaptive Balanced Merkle Tree (ABM tree). This structure combines a balanced binary tree with a Merkle tree to improve storage scalability and facilitate intra-block querying of historical data. In [233], the authors address the efficiency issues of blockchain data queries by introducing flexible query interfaces for Ethereum blockchain data, such as range and top-k queries, which are not supported by the native Ethereum client. The B+ tree has also been used to improve search capabilities and reduce storage costs [437]. Implemented on the Ethereum Geth 1.8 client, it supports top-k, range, and equality searches in real time, demonstrating efficient search functionality and low storage costs. To support efficient intra-block queries, recent research suggests replacing the Merkle tree with a new query scheme that includes additional fields in the block header. This method allows for optimizing inter-block queries, achieving high execution efficiency with minimal storage [217]. Further improvements to traditional blockchain query methods have been proposed to enhance search efficiency for both inter- and intra-block queries [239]. The proposed method uses a novel data structure within the Hyperledger Fabric framework, incorporating two indices: an Abstract-Trie index for efficiently querying original data features and an Operation-Record List index that links operation records to their corresponding data. To decrease query times within blocks and improve user experience in blockchain-based electronic trading systems, modifications to the B-tree structure were introduced within the Ethereum framework, utilizing a B-Key-Value index directory to store transaction and block numbers as key-value pairs [415].

Although these works provide effective mechanisms for optimizing intra-block queries, they were primarily designed for public blockchain systems and have not yet been applied to the context of the food supply chain. Based on these approaches, we aim to optimize traceability queries, particularly within each block of the blockchain record, to handle the massive transaction data related to food traceability and improve query performance.

6.3 Proposed Model

This section introduces our proposed solution designed to enhance intra-block query efficiency within a blockchain-based food supply chain network. The model aims to overcome existing limitations in transaction search speed and scalability by restructuring the blockchain's data format and integrating a novel MerkleB+ tree (MB+ tree) indexing technique. We focus on redesigning the blockchain architecture to support high-frequency data recording and fast retrieval, essential for real-time traceability and transparency across all stages of the supply chain.

Our proposed model consists of three core components:

1. Blockchain network designed for food supply chain case with high data transaction volumes management.

2. MB+ tree index structure within each block to support efficient intra-block queries.
3. Traceability query process performed by consumers.

6.3.1 Blockchain Technology Design

In our design for intra-block query optimization, blockchain technology functions as a tamper-proof and transparent distributed ledger, ensuring secure and verifiable traceability of products across each stage of the food supply chain. The data generated from food production, processing, transportation, and distribution is modeled as continuous time series. This results in a high volume of real-time transactions, all of which are recorded as structured entries on the blockchain. Each block within our network aggregates a substantial batch of these transactions, corresponding to the operational events that occur at each time interval.

To enable efficient intra-block querying, we redesigned the structure of blockchain transactions to support effective data storage by integrating a B+ tree indexing mechanism with the Merkle tree for efficient data retrieval within each block. In our implementation, each transaction includes two components essential for data search: a key and a value. The key is defined as the unique Product ID, which serves as the primary identifier for traceability operations and the value consists of the remaining traceability-related attributes (see Figure 6.1).

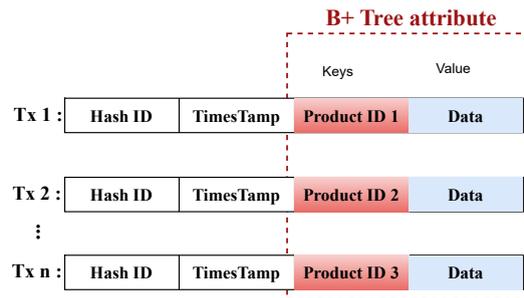


FIGURE 6.1: Transaction structure in the blockchain network

By designing the transaction format to support this indexing model, we allow queries to directly target relevant transaction data within a block, significantly reducing search time compared to sequential scanning. This is especially valuable for traceability queries, where locating a specific product's record quickly is essential for safety, auditing, or regulatory purposes. The structured integration of MB+ tree logic into the blockchain design marks a key innovation in our approach, bridging performance and integrity in high-volume, real-time supply chain systems.

6.3.2 MB+ Tree Structure Design

To accelerate intra-block queries while preserving data integrity, we introduce a hybrid indexing structure called the MerkleB+ tree (MB+ tree). The MB+ tree structure is embedded directly within each block and is constructed over the batch of transactions stored therein. Specifically, all transaction keys (Product IDs) are sorted and inserted into the B+ tree, forming the leaf nodes and the internal nodes maintain pointer references and key ranges to facilitate logarithmic-time traversal and search. Once the B+ tree is built, a Merkle tree is layered on top by computing

cryptographic hashes. These hashes are generated from the leaf nodes upward, forming the internal nodes of the Merkle tree and ultimately the Merkle root. This hybrid structure combines the fast search capability of B+ trees with the cryptographic integrity guarantees of Merkle trees (see Figure 6.2).

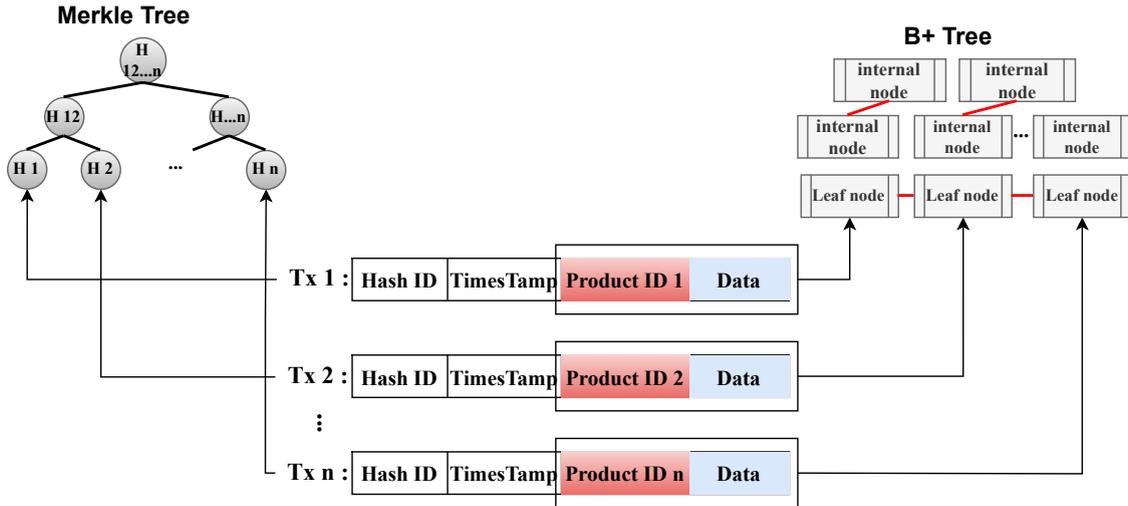


FIGURE 6.2: Merkle and B+ tree in the block structure

By leveraging this design, the system improves transaction retrieval within each block, enhances intra-block query efficiency, and ensures that traceability data is securely stored and accurately retrieved in response to consumer queries. This tree structure combines:

- **Merkle Tree Component:** Provides cryptographic verification of transaction integrity using hash functions (e.g., SHA-256). Each leaf node stores a hash of transaction data, and internal nodes contain hashes of their child nodes, until we find the Merkle root.
- **B+ tree Component:** Enhances intra-block search efficiency by organizing transaction entries in a balanced and sorted tree, allowing logarithmic time complexity ($O(\log N)$) for search, insertion, and deletion operations.

This new structure still leverages cryptographic hashing (SHA-256) to guarantee data integrity, enabling efficient transaction verification by summarizing all data into a single root hash [220]. Meanwhile, it offers a balanced and self-adjusting data structure commonly used in databases, ensuring optimal search and update performance. Overall, the MB+ tree enables rapid data access with logarithmic complexity $O(\log N)$, representing a significant improvement over native blockchain designs lacking indexing support.

6.3.3 Traceability Query Process

The traceability query process in our blockchain network is designed to efficiently retrieve historical data about food products from the ledger, thereby enhancing search performance within the food supply chain. The process begins when a consumer submits a query based on Product ID of the specific item serves as the query key, and the corresponding transaction data is retrieved

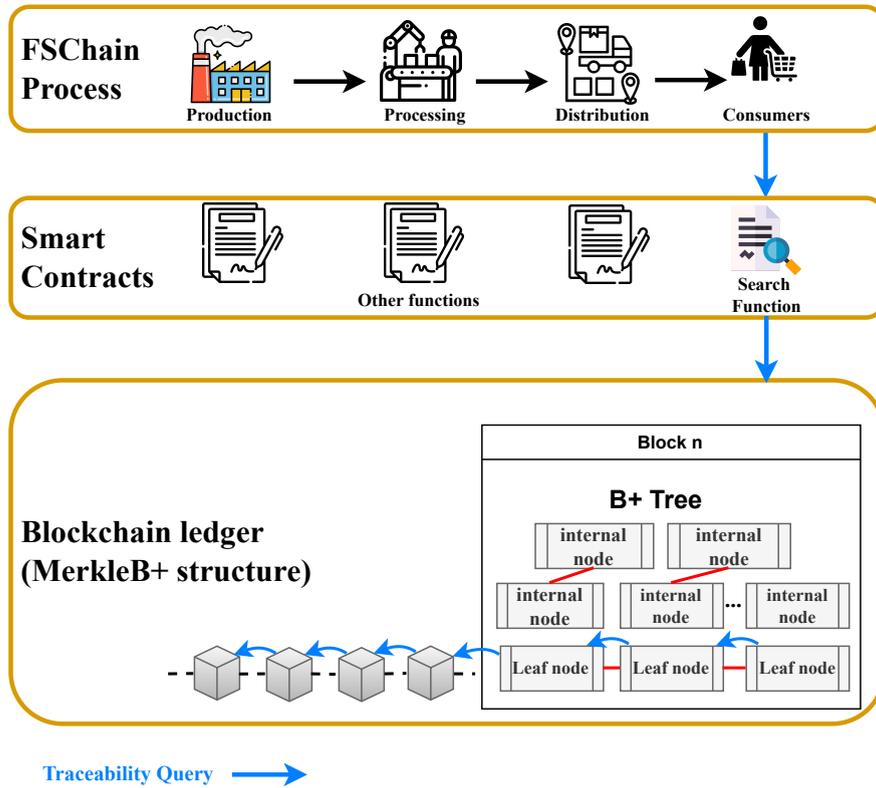


FIGURE 6.3: Traceability query process

as the result with the search function that utilizes the B+ tree index within each block. The overall query process using our proposed method is illustrated in Figure 6.3.

The traceability query workflow based on a consumer or stakeholder request proceeds as follows:

1. **Query Submission:** The consumer initiates a query using a specific Product ID (e.g., Product ID = 101), which is passed to the smart contract.
2. **Intra-block Search:** For each block, the MB+ Tree is traversed to locate relevant leaf nodes that point directly to matching transactions.
3. **Transaction Extraction:** All identified transactions within the blocks are retrieved using the efficient MB+ Tree structure.
4. **Response Construction:** The system assembles a verified traceability response, which is then returned to the consumer.

Within each block, a MB+ tree index is used to organize and retrieve big transaction data, enabling the system to efficiently locate data relevant to a consumer query.

6.4 Experiments

The proposed hybrid structure was implemented and tested on the Hyperledger Fabric framework. We introduced necessary modifications based on our business logic or our simulation, focusing on changes to the block structure, as well as the storage and querying of large-scale transaction data.

6.4.1 Settings

Hyperledger Fabric provides the flexibility to define custom query logic within the chaincode. In our implementation, we modified the data storage structure in each block to integrate a MB+ tree, which serves as an indexing structure for the transaction data [32].

To support both the native (sequential scan) and the proposed (indexed) query approaches, we developed two distinct functions: one for storing transactions and another for executing traceability queries. These functions were implemented in the chaincode.go file, where the MB+ tree indexing logic was embedded and then deployed and tested using CLI commands in the Hyperledger Fabric test network.

We executed multiple simulation scenarios using our blockchain model under varying configurations, with a focus on two key factors that affect intra-block query performance: transaction volume and target transaction volume.

- **Blockchain Size:** Indicates the number of blocks within the blockchain ledger. We fixed this at 5 blocks, as our main focus was on intra-block query performance.
- **Transaction Volume:** Refers to the number of transactions within a block. We evaluated blocks containing 200, 400, 600, 800 and 1000 transactions.
- **Target Transaction:** For each test scenario, we perform a query targeting one specific transaction within each block.

Table 6.2 summarizes the scenario configuration based on varying transaction sizes to evaluate the effectiveness of the proposed MB+ tree indexing structure.

Scenario	Transaction Size (per Block)	Block Size	Target Transactions
Scenario 1	200	5 Blocks	1 transaction per block
Scenario 2	400	5 Blocks	1 transaction per block
Scenario 3	600	5 Blocks	1 transaction per block
Scenario 4	800	5 Blocks	1 transaction per block
Scenario 5	1000	5 Blocks	1 transaction per block

TABLE 6.2: Experimental scenarios based on varying transaction sizes per block

In these experiments, we disabled the state database and all external indexing features provided by Hyperledger Fabric. This allowed us to simulate the query process solely through the MB+ tree mechanism and to evaluate the improvements in traceability query performance.

6.4.2 Results and Analysis

The performance of the two methods is evaluated based on the processing time of the queries. After generating the datasets and establishing the blockchain ledger in our test network, the search process is initiated, and the time taken to retrieve traceability information for a specific product is recorded for both methods. The results of these evaluations are presented in Figure 6.4 and Table 6.3, which illustrate the performance for both methods across all scenarios.

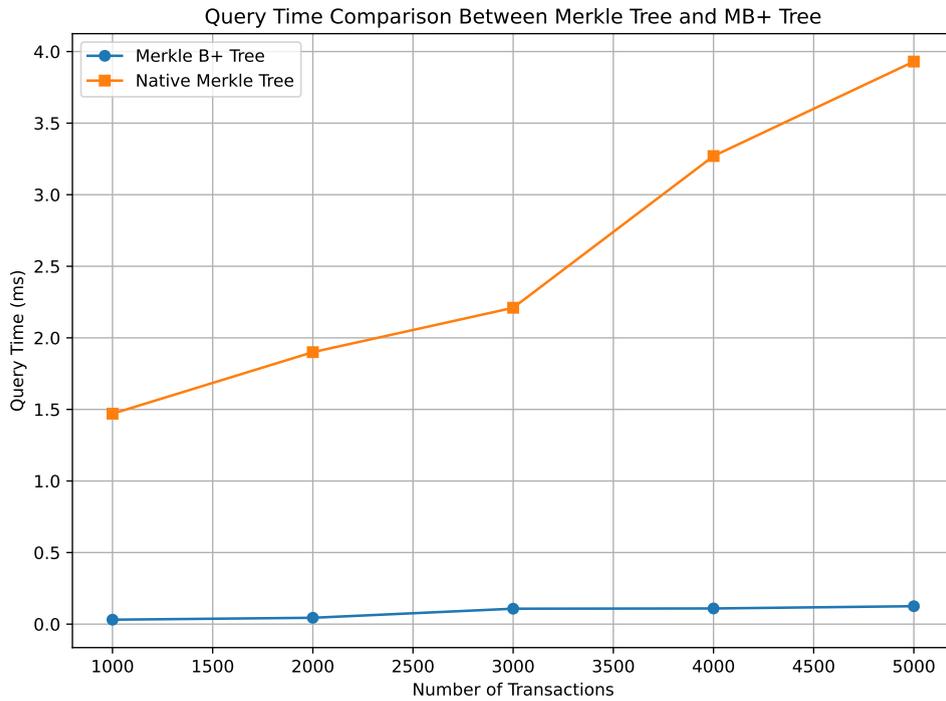


FIGURE 6.4: Query time comparison between Merkle tree and MB+ tree

Scenario	Number of Transactions	MB+ Tree (ms)	Native Merkle Tree (ms)
Scenario 1	1000	0.031	1.47
Scenario 2	2000	0.044	1.90
Scenario 3	3000	0.108	2.21
Scenario 4	4000	0.109	3.27
Scenario 5	5000	0.125	3.93

TABLE 6.3: Query time comparison between MB+ tree and native Merkle tree

From Figure 6.4 and Table 6.3, the query performance of the two methods shows a significant difference across all blockchain sizes. The optimized method using the MB+ tree structure significantly outperforms the traditional method based on the native Merkle tree. For the native Merkle tree method, the search time ranges from 1.47 ms to 3.93 ms as the transaction size per bloc increases from 200 to 1000 blocks. In contrast, the optimized method demonstrates much more stable performance, with search times remaining below 0.125 ms, even at the largest transaction size per block of 1000 transactions. This substantial improvement in query efficiency highlights the effectiveness of the MB+ tree structure in handling larger datasets, making it a more scalable solution for real-world applications.

The results also indicate that the traditional method experiences a linear increase in search time as the transaction size grows for example in complex supply chains, which can become a bottleneck for systems requiring real-time traceability. On the other hand, the optimized method maintains consistently low search times, regardless of the blockchain size, due to the efficient features and retrieval capabilities of the MB+ tree. This stability is crucial for applications in the food supply chain, where timely access to traceability data is essential to ensure food safety and compliance with regulatory standards.

6.4.3 Discussion

The experimental results clearly demonstrate the superiority of the proposed MB+ tree structure over the traditional Merkle tree when it comes to intra-block query performance. By embedding an indexing mechanism directly into the block structure, the MB+ tree significantly reduces the time required to search for and retrieve transaction data, especially under high-volume scenarios. This performance gain becomes increasingly pronounced as the number of transactions per block grows, showcasing the scalability and efficiency of the hybrid design.

These improvements are particularly important for blockchain-based systems in domains such as food supply chain management, where traceability queries must be executed quickly and reliably. In such contexts, delays in retrieving traceability data can have serious implications, especially during food recalls, compliance checks, or real-time audits. The ability to perform fast, targeted queries on large volumes of transaction data directly within a block supports better decision-making and enhances consumer safety and trust.

Moreover, the hybrid MB+ tree structure addresses a well-known limitation of traditional blockchain designs which is the lack of efficient internal indexing. Most blockchain platforms, including Hyperledger Fabric, rely on external state databases or full block scans for data retrieval. While effective in small-scale deployments, these approaches do not scale well when transaction volumes increase. Our approach eliminates this dependency by embedding the indexing logic into the chaincode and block data structure itself, enabling faster, on-chain traceability queries without external systems.

Despite these promising results, several limitations remain in the current implementation where the integration of indexing logic into the chaincode and the block structure introduces additional complexity to the smart contract development process and affect security. Overall, the results validate that intra-block indexing with the MB+ tree structure is a promising direction for enhancing traceability in blockchain systems.

6.5 Conclusion

In this chapter, we addressed the limitations of intra-block queries when retrieving traceability data from the blockchain ledger which is an issue that directly impacts consumer safety. To overcome this challenge, we proposed a new hybrid structure that integrates the B+ tree with the Merkle tree. This combination leverages the integrity and security properties of the Merkle tree along with the logarithmic search efficiency of the balanced B+ tree. We introduced modifications to the transaction data structure to support our design, ensuring that each transaction contains traceability information about food products and can be efficiently retrieved in

response to consumer queries. The performance of our proposed solution was evaluated under various scenarios, demonstrating notable improvements in query efficiency compared to the native blockchain structure.

CONCLUSION AND PERSPECTIVES

In this thesis, we employed indexing techniques for big data management in the food supply chain, with a particular focus on optimizing the traceability query process in blockchain-based systems to ensure food safety. In this conclusion, we provide an overview of the contributions made and suggest potential directions for future research.

The first part was dedicated to presenting the state of the art and establishing the necessary foundations of our thesis by introducing the food supply chain process and the concept of food safety within it, as well as exploring blockchain technology and its role in enhancing data security and retrieval. Furthermore, the review of recent studies in this area allowed us to identify the problems and challenges faced by existing blockchain-based food supply chain traceability query systems.

The second part of this thesis focused on our contributions based on indexing techniques, which aimed at addressing the challenges of query inefficiency in blockchain-based food supply chains. From the review of existing studies on blockchain traceability query optimization, we identified the main limitation of blockchain technology in terms of the sequential query process, which requires an optimization solution to enhance decision-making and improve food safety for consumers.

To tackle this challenge, we first proposed a blockchain-based traceability system that optimizes inter-block queries through B-tree indexing. This was achieved by modifying the transaction data structure to include new attributes related to food products and by creating a function that generates data stored in an external B-tree index. In our solution, the traceability query process begins in the B-tree to locate the relevant blocks, then moves to the blockchain ledger for intra-block queries to provide consumers with traceability data. Evaluation through different scenarios and datasets showed significant improvements in search time for historical food product data compared to traditional methods, as irrelevant blocks are skipped and the query process is streamlined.

Our second solution aimed to further enhance traceability queries particularly inter-block type by integrating an NLP model with B+ tree indexing. The NLP model interprets consumer queries to identify the target stage of the supply chain, while the B+ tree index locates the corresponding blocks, ensuring the search is executed only within relevant parts of the ledger. This system was implemented on Hyperledger Fabric and tested under various configurations, yielding promising results.

Another challenge lies in the limitations of intra-block queries and the large number of transactions within each block. To address this challenge, the third contribution focuses on optimizing

intra-block queries in scenarios involving high transaction volumes per block. We propose a combination of the B+ tree architecture with the Merkle tree, combining the safety and security properties of the Merkle tree with the algorithmic search efficiency of the B+ tree. This design reduces query time and improves performance compared to traditional methods. Overall, these three contributions significantly contribute to the development of blockchain-based traceability systems by enhancing query efficiency, scalability, and reliability in food supply chain applications.

However, although our system optimizes traceability queries in blockchain-based FSC and enhances food safety for consumers, future research could focus on exploring alternative indexing structures with greater efficiency for insertion, update, and search operations, as well as support for multi-dimensional or hybrid queries. Another promising direction involves integrating advanced AI techniques, such as transformer-based models and large language models (LLMs), including fine-tuning, which have shown strong capabilities in understanding complex natural language inputs and reducing misclassification rates across food supply chain stages. Furthermore, enriching user queries by extracting additional contextual information alongside the food supply chain stage could enable more detailed and multi-criteria traceability searches in the blockchain ledger, thereby improving the precision of the returned data for consumers.

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AUTHOR'S PUBLICATION

❖ International publications

- ❑ **Ilyas Ziaya**, Brahim Farou, Zineddine Kouahla, and Hamid Seridi, "A Blockchain and B-Tree Indexing Approach to Improve Traceability and Query Efficiency in Food Supply Chain", Cluster Computing, link: <https://link.springer.com/article/10.1007/s10586-025-05631-3>.
- ❑ **Ilyas Ziaya**, Brahim Farou, Zineddine Kouahla, and Hamid Seridi, "Improving Traceability Query in Blockchain-Based Food Supply Chain Systems Using NLP and B+ Tree Indexing", Knowledge and Information Systems, Current statue:Under Review.

❖ International Communications

- ❑ **Ilyas Ziaya**, Brahim Farou, Zineddine Kouahla, and Hamid Seridi, "HyperMB+ Tree: A High-Performance Blockchain Data Index for Efficient Search in Food Supply Chains", The 7th International Conference on Pattern Analysis and Intelligent Systems (PAIS), 2025, pp. 1–6, IEEE.
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- ❑ **Ilyas Ziaya**, Ala-Eddine Benrazek, Brahim Farou and Kouahla Zineddine "Data Query in Food Supply Chain With Blockchain Technology", The 6th International Hybrid Conference on Informatics and Applied Mathematics (IAM'23), University 8 Mai 1945, Guelma, December 6–7, 2023.

❖ National Communications

- ❑ **Ilyas Ziaya**, Brahim Farou, Zineddine Kouahla, and Hamid Seridi, "AI in Blockchain-Based Food Supply Chain Systems: Enhancing Transparency, Traceability, and Security", The National Conference of Innovation on Data Engineering and AI Science (IDEAS), Oran, Algeria, June 17–18, 2025.
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- ❑ **Ilyas Ziaya**, Brahim Farou, Zineddine Kouahla, and Hamid Seridi, "Enhancing Traceability Query in Blockchain-Based Food Supply Chains Using a Merkle B+ Tree Indexing Technique", The National Conference on Computational Engineering, Artificial Intelligence and Smart Systems (NCCEIASS2024), Tamanrasset, Algeria, December 10–12, 2024.