



Bibliometric Research of Blockchain in Biotechnology

A Strategic Bibliometric Analysis and Conceptual Integration Framework for the Biotechnological Future

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ABSTRACT

This thesis uses a dual-method approach that combines qualitative conceptual framework creation and quantitative bibliometric research to investigate the intersection between Blockchain Technology (BCT) and Biotechnology. The study examines the use of blockchain in six different biotechnology sectors, genetic, environmental and bioenergy, medical, marine, cosmetic and pharmaceutical, as also agri-food biotechnologies, based on peer-reviewed Scopus-indexed publications published between 2020 and 2025. The bibliometric analysis yielded a total of 8.302 articles. A growing academic emphasis on traceability, data security, smart contracts, and decentralized process management inside biotech systems was revealed by this research, which the use of VOSviewer to map scientific output patterns, co-authorship networks, theme clusters, and keyword and country co-occurrences.

To bridge theory with practice, the thesis introduces a conceptual framework for blockchain implementation tailored to the biotechnology sector. With a primary focus on Carbios, a French biotech business that is at the forefront of enzymatic PET plastic recycling, this paradigm is validated by a thorough examination of real-world case studies. The Carbios scenario illustrates how blockchain may assist the goals of the circular economy by securing the provenance of plastic waste, automating quality testing based on smart contracts, and improving environmental impact reporting. Further examples of how blockchain infrastructure can support regulatory compliance, transparency, and consumer trust across various biotechnology verticals include Medicalchain's decentralized patient health records, Merck's blockchain-enabled pharmaceutical traceability, JBS the transparent livestock farming platform and the "Thank My Farmer" app for agri-food transparency.

However, considerable obstacles remain, namely scale constraints, interoperability complications, and regulatory ambiguity. The thesis suggests mitigating techniques include automation of regulatory compliance processes, hybrid blockchain systems, and focused stakeholder education. Overall, the results show that blockchain has the potential to revolutionize biotechnology and provide a roadmap for its ethical, sustainable, and strategic application in biotechnological ecosystems of the future.

Keywords: Blockchain; Biotechnology; Supply Chain; Bibliometric Analysis.

RESUMO

Esta tese utiliza uma abordagem de método duplo que combina a criação de um quadro conceptual qualitativo e a investigação bibliométrica quantitativa para investigar a interseção entre a Tecnologia Blockchain (BCT) e a Biotecnologia. O estudo examina a utilização da blockchain em seis setores diferentes da biotecnologia: genética, bioenergia ambiental, médica, marinha, cosmética e farmacêutica, bem como nas biotecnologias agroalimentares, com base em publicações indexadas pela Scopus e revistas por pares, publicadas entre 2020 e 2025. A análise bibliométrica resultou num total de 8.302 artigos relevantes. Esta pesquisa revelou uma crescente ênfase académica na rastreabilidade, segurança de dados, contratos inteligentes e gestão descentralizada de processos dentro dos sistemas biotecnológicos, utilizando o VOSviewer para mapear padrões de produção científica, redes de coautoria, clusters temáticos e coocorrências de palavras-chave e países.

Para unir a teoria à prática, a tese apresenta um quadro conceptual para a implementação da blockchain adaptado ao setor da biotecnologia. Com foco principal na Carbios, uma empresa francesa de biotecnologia que está na vanguarda da reciclagem enzimática de plástico PET, este paradigma é validado por uma análise aprofundada de estudos de caso reais. O cenário da Carbios ilustra como a blockchain pode ajudar os objetivos da economia circular, garantindo a proveniência dos resíduos plásticos, automatizando os testes de qualidade com base em contratos inteligentes e melhorando os relatórios de impacto ambiental. Outros exemplos de como a infraestrutura blockchain pode apoiar a conformidade regulatória, a transparência e a confiança do consumidor em vários setores da biotecnologia incluem os registos de saúde descentralizados da Medicalchain, a rastreabilidade farmacêutica habilitada por blockchain da Merck, a plataforma transparente de pecuária da JBS e o aplicativo “Thank My Farmer” para transparência agroalimentar.

No entanto, ainda existem obstáculos consideráveis, nomeadamente restrições de escala, complicações de interoperabilidade e ambiguidade regulamentar. A tese sugere que as técnicas de mitigação incluem a automatização dos processos de conformidade regulamentar, sistemas híbridos de blockchain e educação focada das partes interessadas. Em geral, os resultados mostram que a blockchain tem o potencial de revolucionar a biotecnologia e fornecer um roteiro para a sua aplicação ética, sustentável e estratégica nos ecossistemas biotecnológicos do futuro.

Keywords: Blockchain; Biotecnologia; Cadeia de fornecimento; Análise Bibliométrica.

1. INTRODUCTION

1.1 Blockchain Concept

The concept of blockchain was introduced by Satoshi Nakamoto in 2008 (Nakamoto et al., 2008). Blockchain is a decentralized, impenetrable digital ledger. It eliminates the need for a central authority by allowing a network of participants to record transactions in a shared ledger. A chronological "chain" of data is created by grouping each transaction into a "block," which is then cryptographically connected to the block before it. This structure offers high security and trust by guaranteeing that once information is recorded, it cannot be changed retroactively without network consensus according to Figure 1 (Yaga et al., 2019).

Beyond its origins in financial systems, blockchain technology has increasingly been explored as an enabling digital infrastructure for complex, data-intensive sectors such as biotechnology. Strong assurances of data integrity, traceability, and limited access are necessary for biotechnological systems that depend on extremely sensitive data, such as genomic sequences, clinical trial records, biomanufacturing logs, and regulatory documents. Blockchain technology provides a decentralized way for various parties, including research labs, manufacturers, healthcare facilities, and supply chain partners, to safely record, distribute, and validate such data. Blockchain can lower the risk of data tampering, increase actor confidence, and facilitate adherence to strict regulatory frameworks governing the biotechnology and life-science industries by guaranteeing the immutability and transparent provenance of biological data and materials (An et al., 2023).

Together, these applications highlight blockchain's role not merely as a supporting digital tool but as a foundational trust layer capable of reshaping biotechnological ecosystems. By integrating blockchain with biotechnology, organizations can enhance transparency, security, and sustainability across research, production, and distribution processes.

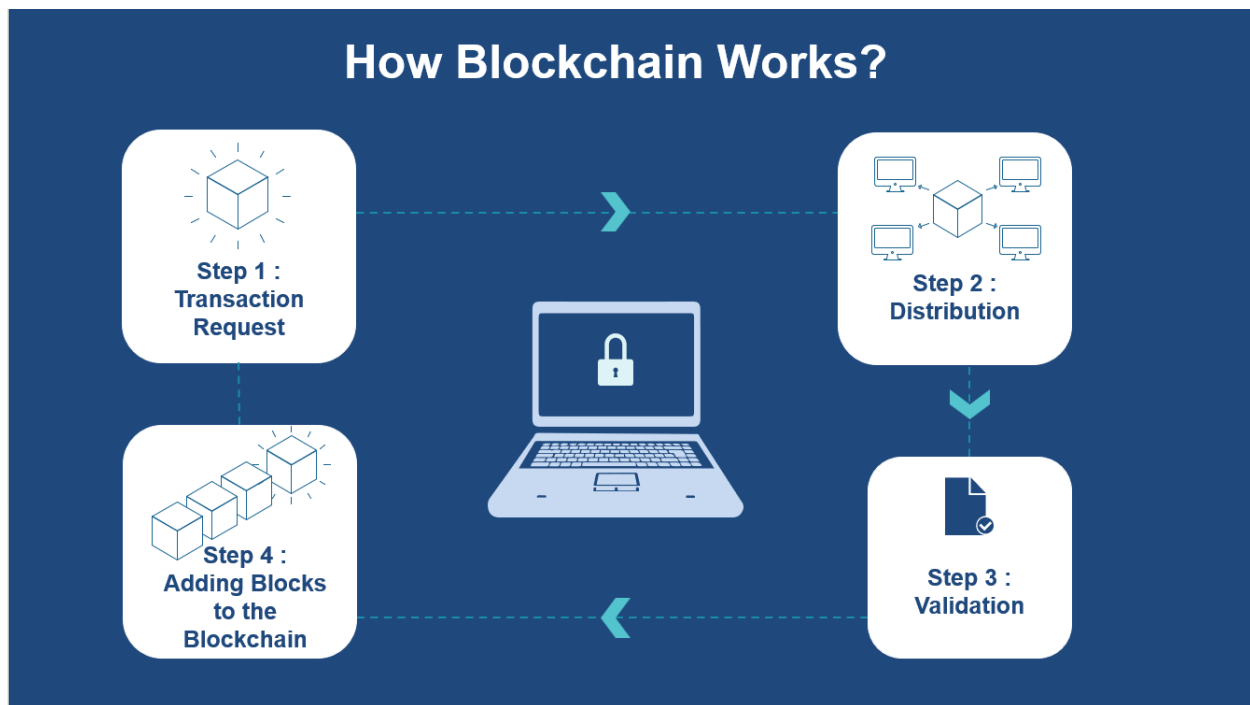


Figure 1: Blockchain working structure (A Beginner’s Guide to Understand Blockchain Technology | by SoluLab | Nerd For Tech | Medium, 2024).

The blockchain working structure works as follows:

- **Step 1: Transaction Request**

The blockchain process begins with a transaction request, which represents the creation of a new, verifiable event within the system. A transaction in the context of biotechnology refers to the registration of crucial operational or scientific data rather than a financial exchange. Every significant action in the biotechnology value chain can be converted into a blockchain transaction. Transaction requests are generated, for instance, when a shipment of temperature-sensitive vaccines begins, biological samples are stored in a cold-chain facility, or gene therapy items are delivered to a hospital. Temperature logs, batch or sample identification numbers, geographic location, timestamps, and the identities of authorized persons involved in the process are examples of structured metadata that are frequently included in these transactions, By capturing these events at the moment they occur, blockchain ensures data integrity from the very first stage of the process, reducing risks of data loss, manipulation, or retrospective alteration (Lam et al., 2020).

- **Step 2: Distribution**

Once a transaction request is created, the information is distributed across the blockchain network through a peer to peer architecture. At this point, the transaction is disseminated to several nodes, which are separate computers run by authorized biotechnological ecosystem participants. These nodes could be owned by manufacturers, shipping companies, regulatory authorities, hospitals, research facilities, or quality control labs, depending on the application. To guarantee that everyone has access to the same real-time data, each node keeps a synced copy of the ledger (Lam et al., 2020).

In biotechnology supply chains, this distributed visibility is particularly valuable. For instance, temperature fluctuations or delivery delays may jeopardize the safety of cell-based therapies. Blockchain reduces information asymmetry and stops any single entity from monopolizing or changing records by simultaneously sharing transaction data with all stakeholders. Healthcare providers can confirm product integrity before administration, and regulatory agencies can keep an eye on compliance in real time. Transparency and collaboration throughout intricate, multi-actor biotechnology networks are strengthened by this shared access (Lam et al., 2020).

- **Step 3: Validation**

After distribution, the transaction enters the validation phase, where network nodes verify its authenticity and compliance with predefined rules. Depending on whether the blockchain is public, private, or consortium-based, several consensus methods are used for validation. Permissioned blockchains use energy-efficient consensus methods instead of Proof of Work in most biotechnology applications, enabling quicker and more sustainable validation procedures.

Validation criteria are often closely linked to regulatory and quality requirements. In pharmaceutical logistics, for instance, nodes may automatically confirm whether vaccines were handled by qualified workers, whether delivery schedules were adhered to, and whether the necessary temperature range (2–8 °C) was maintained. Similar to this, validation in clinical studies can verify that experimental protocols were correctly followed or that patient consent was gained prior to data access. Unreliable or non-compliant data never enters the blockchain because only transactions that satisfy all predetermined technological, ethical, and legal requirements are authorized (Lam et al., 2020).

- **Step 4: Adding Blocks to the Blockchain**

Once validated, the transaction is grouped with others into a block, which is then permanently added to the blockchain. An unchangeable chain of records is created when each block is time-stamped and cryptographically connected to the one before it via a hash. This structure makes tampering computationally impossible by ensuring that any attempt to change historical data would entail changing all subsequent blocks.

In biotechnology, this immutability is crucial for maintaining trustworthy records across long and complex product lifecycles. Blockchain blocks can register biomanufacturing characteristics across production batches, safeguard vaccination traceability data, and record the gathering and processing of genetic samples. For instance, blockchain generates a comprehensive, auditable history that promotes patient safety and regulatory compliance in advanced therapy medical products (ATMPs), as materials transition from laboratory development to clinical application. Blockchain offers a strong integrity layer that improves transparency, traceability, and confidence in life sciences systems by maintaining an immutable record of scientific, logistical, and operational data (Lam et al., 2020).

1.1.1 Advantages of BCT

In contrast to traditional centralized systems, where every transaction requires verification by a central trusted authority, BCT enables decentralization by eliminating the need for intermediaries and instead relying on consensus mechanisms to maintain data integrity and consistency across distributed networks. One of the key features of blockchain is its persistence, while transactions can be quickly verified, once they are added to the blockchain, they are nearly impossible to alter or reverse. Additionally, anonymity is supported through generated addresses allowing users to interact with the blockchain without revealing their identities, However, it's important to note that blockchain does not offer complete privacy due to certain inherent limitations, as transaction histories are fully transparent and permanently recorded, making it possible to trace and link addresses through behavioral patterns, regulatory entry points, and advanced data analytics techniques. Finally, the credibility of transactions is safeguarded through consensus algorithms and cryptographic hashing techniques that link each block to its predecessor, ensuring that any attempt to tamper with data is costly and unpredictable. This architecture solidifies the immutability and trustworthiness of the blockchain (An et al., 2023).

1.1.2 Challenges and Disadvantages of Blockchain Technology

Despite its advantages, BCT faces several significant challenges that hinder widespread adoption. One major issue is the high consumption of hardware and energy, especially in public blockchains using Proof of Work (PoW), where energy use can surpass that of entire countries, such as Bitcoin's usage exceeding Norway's annual power consumption (Habib et al., 2022). Additionally, high costs related to infrastructure, including robust computing systems and secure network nodes, make implementation expensive. The complexity of execution also presents a barrier, as integrating blockchain into existing systems demands substantial IT modifications and comprehensive staff training. Finally, regulatory uncertainty persists, with unclear legal frameworks in many countries slowing adoption due to evolving policies on taxation, compliance, and security standards (Habib et al., 2022).

1.1.3 The Different Types of Blockchain Technology

- **Public Blockchain:** A public blockchain is accessible to everyone, allowing any anonymous node to join, without requiring any trust from participants. All nodes receive a public broadcast of transactions, and any network node can take part in the consensus process to verify the blocks (Alghazwi et al., 2022).

Use Cases: Cryptocurrencies, Decentralized finance (DeFi), verifiable voting systems.

- **Private Blockchain:** After being pre-selected and screened, nodes are trusted once they join the network. The content of blockchain transactions is more privately protected thanks to the access control mechanism. Higher performance in terms of block confirmations is another benefit of this kind of blockchain (Alghazwi et al., 2022).

Use Cases: Supply chain tracking within a company, Internal data management, and Enterprise-level applications like audits.

- **Consortium Blockchain** combines the first two by balancing trust and efficiency, with a pre-selected set of nodes overseas managing the ledger. To join the network, nodes need permission, like private blockchains. When a selected group of nodes comes to an agreement, blocks and transactions are validated. The consensus mechanism's predetermined rules define the precise procedure (Alghazwi et al., 2022).

Use Cases: Cross-organizational supply chain management, Interbank payment systems, Collaborative research platforms (Alghazwi et al., 2022).

- **Hybrid Blockchain:** Both public and private choices are combined in hybrid blockchains. They can be tailored to different access levels and, therefore, offer a balance between the decentralized nature of public blockchains and the control of private ones (Paul et al., 2021).

Use Cases: Public sector applications with sensitive citizen data, Enterprise solutions requiring transparency and confidentiality, and Real estate and asset management (Paul et al., 2021).

- **Sidechains:** are secondary blockchains that have a two-way peg connecting them to other blockchains, a two-way peg is a mechanism that permits assets to be transferred back and forth between the main and the sidechain at a predetermined or fixed exchange rate (Singh et al., 2020).

Use Cases: Scaling solutions for existing blockchains, especially specialized applications like gaming or DeFi (Singh et al., 2020).

1.2 Biotechnology

Biotechnology is a multidisciplinary field that utilizes living organisms or their components to create products and processes that benefit humanity. It has advanced significantly in recent years and incorporates elements of molecular biology, genetics, biochemistry, and engineering, among other scientific fields (Bentahar, 2023).

According to another thorough definition, biotechnology is using biological science and engineering concepts to create new products from biologically derived basic materials, such as foods or even vaccines. Stated differently, it can also be described as the application of organisms or their byproducts to alter or enhance human environments and health (Verma et al., 2011).

Biotechnology encompasses several specialized branches, each focusing on different applications. For the present study, the focus was more dedicated on specific sectors shown in Figure 2. These branches illustrate the vast scope of biotechnology and its crucial role in developing several industries, including healthcare, industry, agriculture, and environmental management.

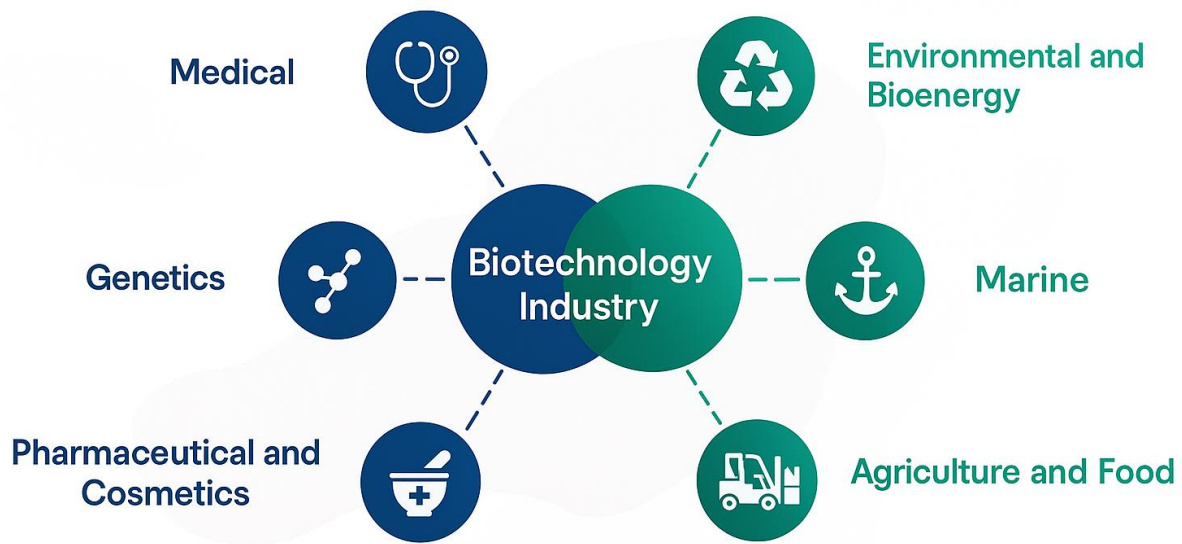


Figure 2: The different types of Biotechnology.

- **Environmental Biotechnology and Bioenergy**

This integrated discipline uses biological processes to address environmental issues and renewable energy, especially those involving microbes, enzymes, and biomass. To promote environmental sustainability and clean energy innovation, it incorporates biotechnological techniques for waste treatment, pollution remediation, and the transformation of organic resources into biofuels, electricity and heat (Ezeonu et al., 2012; Shahbazi & Rahimpour, 2024).

- **Genetics**

Genetics in biotechnology focuses on understanding and manipulating genes to improve organisms. Gene therapy, genetic engineering, and the creation of genetically modified organisms (GMOs) for diverse uses are examples of applications (Moreto Guaitolini et al., 2024).

- **Medical Biotechnology**

This field uses biological systems to create diagnostics and medical supplies. To enhance human health, it involves developing vaccinations, therapeutic proteins, and cutting-edge diagnostic equipment (Bifulco et al., 2025).

- **Marine Biotechnology**

Oceanic species are studied in marine biotechnology to create novel products and procedures. Marine biodiversity supports aquaculture, pharmaceuticals, and environmental sustainability (Daniotti & Re, 2021).

- **Cosmetic and Pharmaceutical Biotechnology**

Biotechnology is transforming medicine and cosmetics with innovative health and wellness approaches. In pharmaceutical biotechnology, researchers use biological systems to create cutting-edge treatments that target diseases at their molecular causes, such as recombinant proteins and monoclonal antibodies. On the other hand, cosmetic biotechnology uses similar skincare advancements to create customized, efficacious beauty treatments through tissue engineering, genetic profiling, and bioengineered chemicals. These disciplines revolutionize internal skin care and healing (Mallela, 2010; Rinaldi, 2008).

- **Agricultural and Food Biotechnology**

Biotechnology is in the heart of the future of agriculture and food. Genetic engineering and other techniques are employed in agricultural biotechnology to increase crop yields, improve nutrition, livestock, and support environmentally friendly methods such as climate-resilient farming and pest-resistant plants. Food biotechnology, which uses microorganisms, enzymes, and genetic approaches to enhance flavor, texture, nutrition, and safety, is revolutionizing how to produce and preserve foods. The world is fed more sustainably, intelligently, and cleanly thanks to these working fields (Ranjha et al., 2022; Falk et al., 2002).

Otherwise, there is another academic recognition of biotechnology classification, which is the color-coded concept. This system is known as the "Rainbow Code" in literature. This method uses different colors to indicate the different biotechnology industries and their respective applications (Kafarski P, 2012).

Here's an overview of the primary colors and their associated fields as shown in Figure 3: (Barcelos et al., 2018).

- Red Biotechnology: Medical & Pharmaceutical Application
- White Biotechnology: Industrial Processes

- Green Biotechnology: Agricultural Innovations
- Gold Biotechnology: Bioinformatics And Data
- Blue Biotechnology: Marine and Aquatic Resources
- Yellow Biotechnology: Manufacturing Food
- Violet Biotechnology: Legal and Ethical Aspects
- Black or Dark Biotechnology: Bioterrorism and Biological Warfare

Types of biotechnology

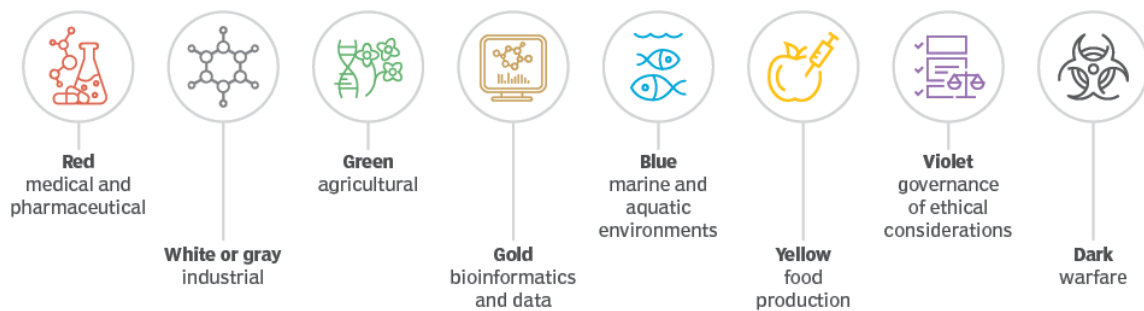


Figure 3: Types of biotechnology based on the Rainbow Code classification (What Is Biotechnology? Definition, Types and Applications | TechTarget, 2022).

1.2.1 Biotechnology Supply Chain Applications

A comprehensive theoretical framework explaining how blockchain can systematically resolve the structural and operational challenges in biotechnology ecosystems is essential for integrating BCT into biotechnology supply chains. Besides a list of technological applications, this framework accommodates the specific needs of various sectors such as genetics, environmental biotech, pharmaceuticals, and agri-food systems. It leverages core blockchain features like decentralization, immutability, transparency, cryptographic security, and smart contract automation (Yavaprabhas et al., 2024).

The following mechanisms are made possible by these fundamental traits:

- **Traceability and Provenance:** Immutable records enable end-to-end visibility of biological materials, from raw inputs (biomass, genetic material) to final products (Varriale et al., 2020).

-
- **Automated Compliance via Smart Contracts:** Smart contracts automate the enforcement of regulatory standards and operating procedures, ensuring real-time compliance with Good Manufacturing Practices (GMP), cold-chain protocols, and bioethical agreements (Daraghmi et al., 2024).
 - **Cryptographic Data Security:** Sensitive genetic, clinical, and proprietary formulation data can be securely stored and shared using cryptographic protections, mitigating risks of data tampering or unauthorized access (Varriale et al., 2020).
 - **Decentralized Consent and Governance:** Blockchain enables patients, producers, or researchers to retain ownership over their data and permissions through programmable consent logs, increasing transparency and trust (Moreto Guaitolini et al., 2024).
 - **Real-Time Monitoring with IoT Integration:** When integrated with IoT devices, blockchain supports the real-time monitoring of environmental and logistical parameters, ensuring the safety and quality of biotechnology products throughout distribution (Sanwar Hosen et al., 2020).

According to this architecture, blockchain is positioned as an integrated digital trust layer that supports the whole biotechnology supply chain rather than as an external technology. It guarantees real-time transparency and verification, synchronizes data amongst stakeholders (consumers, researchers, healthcare providers, producers, and regulators), and automates crucial compliance tasks. A more secure, moral, effective, and sustainable biotechnology ecosystem results from this integration. Global objectives for safety, traceability, regulatory alignment, and innovation are supported by this integrated framework, which addresses both technological and governance challenges in biotechnology supply chains (An et al., 2023).

This thesis will dig into every sector of biotechnology to better understand the applications of BCT in biotechnology supply chains.

1.2.2 Environmental Biotechnology and Bioenergy

The potential of BCT to improve sustainability and efficiency in environmental biotechnology and bioenergy supply chains is becoming more widely acknowledged. Drawing from scientific literature, several key applications and impacts can be listed:

➤ **Enhanced Traceability and Transparency**

Blockchain offers instantaneous and dependable tracking of products and data by creating a permanent, transparent record of supply chain occurrences. This capacity guarantees that biomass feedstocks are procured responsibly and handled per environmental regulations in the bioenergy industry. Such openness makes it easier to monitor emissions and confirm the source of products, which makes it easier to comply with environmental laws (Park & Li, 2021).

➤ **Improved Resource and Waste Management**

Blockchain technology facilitates improved management techniques by capturing comprehensive data on resource consumption and waste production (Varriale et al., 2020). Businesses can keep an eye on resources like electricity and water, maximize their use, and implement recycling and waste management plans. This thorough monitoring aids in initiatives to reduce environmental effect and advance sustainability (M. Wang et al., 2020)

➤ **Operational Efficiency through Smart Contracts**

By automating transactions and enforcing adherence to predetermined criteria, smart contracts eliminate the need for intermediaries. This automation reduces administrative responsibilities and costs in bioenergy supply chains by streamlining procedures like inventory management and payment settlements (Khanfar et al., 2021).

➤ **Encouragement of Low-Carbon Supply Chains**

Throughout the supply chain, blockchain makes tracking and reporting carbon emissions easier. Businesses may identify emission sources and put reduction plans into place by using precise and unchangeable data, which supports international efforts to fight climate change (Sun & Zhang, 2020).

Adopting blockchain can lead to more responsible resource management, reduced environmental impact, and enhanced compliance with regulatory standards.

1.2.3 Genetics

The potential of BCT to improve data security, privacy, and integrity in supply chain management and genetics is being investigated increasingly. Numerous scientific research studies have examined the effects of blockchain applications in these fields.

➤ **Secure Sharing and Storage of Genomic Data**

Strong security measures are required since genetic data contains many sensitive information. The decentralized structure and unchangeable ledger of BCT provide a way to store and share genomic data securely. For example, a private blockchain network that stores reference-aligned reads and genetic variations was presented in a study published in *Genome Biology*. This approach improves data integrity and privacy by giving people ownership over their data and allowing access to academic and healthcare professionals as needed (Gürsoy et al., 2022).

➤ **Improved Consent Management**

It might be difficult to manage patient consent for the use of genetic data. By permanently logging consent transactions, blockchain can expedite this process and guarantee that the patient's desires are followed when using data. This application is best illustrated by the ConsentChain architecture, (ConsentChain is a blockchain-based system that provides a web portal interface to support clinical genomic sharing) which offers a dynamic consent management system that improves transparency and trust between patients and healthcare providers (Albalwy et al., 2021).

➤ **Supply Chain Management in Gene Therapy**

Gene therapy manufacturing and distribution involve complicated supply networks that need careful monitoring to guarantee product integrity. Blockchain's traceability capabilities can monitor every stage, from production to distribution, ensuring adherence to legal requirements and increasing productivity (Lam et al., 2020).

1.2.4 Medical Biotechnology

By improving traceability, transparency, and security throughout the healthcare ecosystem, BCT is proving to be a game-changer in medical biotechnology and supply chain management. Its tamper-resistant and decentralized ledger makes it possible to trace medical products precisely, guaranteeing the integrity and authenticity of things like advanced therapy medicinal products (ATMPs), which need to be handled under strict guidelines (Aguilar-Gallardo & Bonora-Centelles, 2023).

Also, BCT combined with Internet of Things (IoT) devices allows real-time cold chain logistics monitoring, protecting delicate goods from temperature fluctuations. Blockchain secures patient consent data and trial outcomes in clinical trials, improving transparency and regulatory compliance (Nanda et al., 2023).

Additionally, it improves supply chain efficiency by lowering operating costs and delays by automating inventory and order processing and streamlining operations through smart contracts. Overall, blockchain tackles essential issues in medical biotechnology, helping to create a healthcare supply chain that is safer, more effective, and patient-focused (Hu et al., 2023).

1.2.5 Marine Biotechnology

In the fisheries sector, blockchain's decentralized and unchangeable ledger enables comprehensive recording of every stage in the supply chain, from capture to consumer, detailing information such as location, species, and fishing techniques (Alsharabi et al., 2024). This degree of transparency ensures that seafood products are sourced sustainably and responsibly by preventing illegal, unreported, and unregulated (IUU) fishing (Ismail et al., 2023).

According to Ismail (2023), Supply chain integrity is further strengthened by integrating BCT with IoT devices. IoT sensors can track environmental parameters like temperature and humidity during storage and transit, and the blockchain securely stores the data. By ensuring product quality and safety in real time, this monitoring lowers waste and boosts customer confidence.

Projects like AquaLedger exemplify the integration of blockchain with earth observation data to monitor aquaculture environments, promoting sustainable practices and reinforcing stakeholder trust (Home - AquaLedger, 2025).

1.2.6 Cosmetic and Pharmaceutical Biotechnology

The pharmaceutical and cosmetic industries face mounting challenges in securing their supply chains, particularly combating counterfeit products, ensuring traceability, and maintaining transparency. In the pharmaceutical sector, counterfeit and substandard drugs pose a grave threat to public health, causing hundreds of thousands of deaths annually and undermining the credibility of legitimate manufacturers (Zakari et al., 2022; Gaynor et al., 2024). Traditional supply chains often lack transparency, ineffective tracking systems, and vulnerabilities that allow expired or falsified drugs to reach consumers (Emmanuel et al., 2023). BCT offers a transformative solution by enhancing decentralization, traceability, and security through features like cryptographic protection, smart contracts, serialization, and immutable ledgers. It enables the precise tracking of raw materials, medication batches, and distribution channels, reducing risks of tampering and unauthorized alterations (Zakari et al., 2022). These technologies not only strengthen product safety and regulatory compliance but also bolster consumer trust by allowing authenticity verification.

Similarly, the cosmetic industry is an increasingly dynamic and consumer-driven market, grappling with growing concerns about product authenticity, ethical sourcing, and ingredient transparency. With customers demanding more visibility into product origins and often distrusting marketing claims, BCT provides a modern solution by assigning to every cosmetic product a unique digital identity from the moment of manufacturing. This record, stored on an immutable and decentralized ledger, allows stakeholders and consumers to trace the product's journey in real time, ensuring it has not been tampered with during transit (Nehete et al., 2024). Counterfeit cosmetic products, a form of consumer fraud with significant global financial implications, can now be effectively identified and filtered out of the supply chain through blockchain-enabled provenance tracking. Moreover, smart contracts play a pivotal role in ensuring compliance with safety and ethical standards by automating and enforcing agreements between supply chain actors. An example of this innovation in practice is Kozmetika Afrodita, a leading Slovenian cosmetics company, which embraced blockchain to enhance product transparency, consumer trust, and global competitiveness (Prosen & Belak, 2024). Overall, blockchain's integration into both industries' supply chains marks a vital step toward securing product integrity, improving operational efficiency, and protecting end-users from potential harm.

1.2.7 Agriculture and Food Biotechnology

Data reliability is one of the many problems of modern supply chains. These include, among other things, worries about fraud, consumer data protection, environmental effects, supply chain transparency, product quality, logistical difficulties, and food safety. Customers call for more openness in agri-food supply chains as food safety and sustainability concerns grow (Daraghmi et al., 2024).

Fresh food has a limited shelf-life and higher needs than non-perishable goods, making it a sensitive biological matrix. Effective hygienic and quality control procedures are necessary for these fresh goods to satisfy safety requirements. Handling fresh fruit during the procedure may result in slight physiological harm and biochemical impacts, leading to a lower-quality final product (visually, microbiologically, and sensory) (Shiraishi et al., 2025).

Due to increased awareness, consumers focus more on healthful, authentic, safe, and high-quality food than just quantity. According to World Health Organization (WHO) data, over 4,200,000

people globally pass away each year because of consuming contaminated food, and almost 600 million people are impacted annually (R et al., 2024).

The exponential expansion of blockchain, with a compound annual growth rate (CAGR) of 49.75% from 2023 to 2030, illustrates how widely it has been used to transform supply networks. For example, AgriDigital made its first blockchain grain payment in December 2016. AgriDigital's cloud-based system processed 360 million USD in payments to farmers after managing 1.6 million tons of grain for more than 1300 customers. Because of this remarkable success, researchers have started looking into how BCT might enhance agriculture supply chains due to this incredible achievement. More companies have begun implementing blockchain-based supply chain management solutions, including Provenance for tuna tracking and certification, Ambrosus for olive oil monitoring, OriginTrail for Celia dairy, and TE-FOOD for tuna fish (Akram et al., 2024).

1.3. Bibliometric Analysis in Technology Trends

Bibliometric analysis is a well-known and thorough strategy for investigating and analyzing vast volumes of scientific data. It's a quantitative approach to assessing scientific literature, bibliometric analysis examines publications, citations, and other bibliographic data using statistical and mathematical methods. It aids in evaluating the influence of research, patterns, partnerships, and knowledge systems in a particular field. To find trends in academic communication, bibliometric analysis uses techniques including keyword mapping, co-citation analysis, citation analysis, and co-authorship networks (Moral-Muñoz et al., 2020).

In recent years, it has been quite popular in business research. This is because bibliometric tools like Gephi, Leximancer, VOSviewer, and scientific databases like Scopus and Web of Science have become more advanced, accessible, and available (Donthu et al., 2021).

In other words, by rigorously interpreting vast amounts of unstructured data, bibliometric analysis helps map and analyze the evolutionary subtleties of established areas and the cumulative scientific knowledge. Thus, well-executed bibliometric research can establish solid groundwork for expanding discipline in fresh and significant ways. It gives researchers a one-stop perspective, helps them spot knowledge gaps, generates new research ideas, and helps them position their planned contributions to the area (Guo et al., 2021).

Blockchain is crucial in modern technological and economic systems because it enhances transparency, security, and decentralization, addressing critical data integrity and trust challenges. Similar to how bibliometric analysis helps map and analyze the evolution of scientific knowledge, blockchain provides a structured and verifiable way to record transactions and interactions across various domains. By removing the need for a central authority, blockchain ensures data consistency through decentralized consensus mechanisms, much like bibliometric tools that systematically analyze and validate research trends. Just as bibliometric analysis aids researchers in identifying knowledge gaps and shaping future studies, blockchain empowers industries by enabling more efficient, fraud-resistant, and tamper-proof digital ecosystems. This foundational innovation supports advancements in finance, supply chains, healthcare, and beyond, positioning it as a transformative force for data-driven decision-making and secure digital transactions (Pandey et al., 2022).

Bibliometric analysis, meta-analysis, and systematic literature reviews are all methods for organizing and evaluating scientific literature, but they differ in scope and focus. Meta-analysis, often used for theory extension, quantitatively aggregates empirical evidence by analyzing correlations between variables, though it can be affected by study heterogeneity and publication bias. Systematic literature reviews, more suited for specialized fields, involve a methodical but often manual approach to examining smaller studies. Bibliometric analysis, in contrast, provides a broad quantitative overview of a research field by mapping relationships between authors, institutions, and topics. The choice among these methods depends on the review's objectives and the breadth of the analyzed literature (Passas, 2024).

1.4. Objectives

This thesis was created to fulfill a number of research goals because of the growing significance of BCT in the field of biotechnology and the lack of comprehensive, cross-sectoral assessments that are currently available. The study specifically aims to examine the development and evolution of scientific papers on BCT in biotechnology, highlighting important turning points and patterns in its uptake. To achieve this, bibliometric techniques are employed to conduct keyword and co-occurrence analyses, which allow for the identification of major subjects, developing themes, and application domains.

Furthermore, the study maps citation networks and theme clusters using visualization tools like VOSviewer, which helps to make sense of the field's intellectual landscape. The thesis creates a case study on the application of blockchain in pharmaceutical, agri-food, environmental and medical biotechnology in addition to bibliometric insights with the goal of offering concrete proof of its usefulness. When taken as a whole, these goals help achieve the more general objective of providing strategic insights into the opportunities, obstacles, and difficulties related to BCT adoption in biotechnology.

1.5 Case Studies

1.5.1 The Case of Carbios: Enzymatic Recycling and the Future of Plastic Sustainability

As of 2015, approximately 6300 million metric tons of plastic waste had been generated, around 9% of which had been recycled, 12% was incinerated, and 79% was accumulated in landfills or the natural environment. If current production and waste management trends continue, roughly 12,000 million metric tons of plastic waste will be in landfills or in the natural environment by 2050 (Geyer et al., 2017), making it an urgent threat to the environment. In both marine and terrestrial ecosystems, improperly managed plastic builds up and causes microbial community disruption, soil contamination, and wildlife entanglement and ingestion (Kim et al., 2020). Concerns over long-term health impacts have been raised by the discovery of microplastics in food, drinking water, and even human tissues (Ragusa et al., 2021). Additionally, the manufacture and disposal of plastics contribute significantly to greenhouse gas emissions, estimates indicate that by 2050, plastics may be responsible for up to 13% of the world's carbon budget (How Plastics Contribute to Climate Change » Yale Climate Connections, 2019). These effects highlight the urgent need for better waste management, sustainable substitutes, and cutting-edge recycling technology, such as enzyme-based biodegradation techniques.

Carbios is a French biochemistry company that has positioned itself at the forefront of sustainable innovation through its development of enzymatic plastic recycling technologies. The company was founded in 2011 with the goal of creating recycling methods that are biologically inspired and close the loop on plastic waste in order to transform the lifetime of plastics, especially polyethylene terephthalate (PET) (Carbios - Innovating for a True Circular Economy in Plastics, 2025).

By improving the activity of the enzyme Leaf-branch Compost Cutinase (LCC), researchers investigated ways to enhance the enzymatic recycling of PET. When compared to other PET-

degrading enzymes such as *Thermobifida fusca* hydrolases 1 and 2 (BTA1 and BTA2), *Fusarium solani* pisi cutinase (FsC), *Ideonella sakaiensis* PETase (Is-PETase) (Tournier et al., 2020), LCC outperformed all other enzymes tested, reaching an initial PET-specific depolymerization rate of $93.2 \frac{\text{mg}_{\{\text{TAeq}\}}}{\text{h}} \cdot \text{mg}_{\{\text{enzyme}\}}$ at 65 °C, particularly when operating on amorphous PET (Tournier et al., 2020). However, when applied to bottle-grade PET, the reaction stalled after three days, likely due to LCC's reduced thermostability over time despite its high melting temperature. To optimize depolymerization yields, the team sought to improve both the activity and the thermostability of LCC through enzyme engineering, performing targeted mutagenesis on 11 amino acid positions identified through molecular modeling. While most mutations decreased activity, a few, particularly at position F243, showed improvements. They further enhanced thermostability by engineering a disulfide bond (D238C/S283C) to replace a potential metal-binding site, the engineered variant could remain active at 72 °C, which is just below PET's glass transition temperature. This is crucial because PET becomes more amorphous and accessible to enzymes at that range, massively improving depolymerization efficiency by combining the most effective activity-boosting and stabilizing mutations, they developed quadruple mutants (such as ICCG and WCCG) that demonstrated high activity and significantly improved thermostability. These optimized enzymes were tested in pilot-scale bioreactors using post-consumer colored PET waste, which is typically difficult to recycle as summarized Figure 4 the different steps of the sustainable degradation of PET using the LCC-ICCG enzyme. The best variations reached up to 90% depolymerization in less than 10.5 hours after pretreating the PET to improve its surface area and amorphous content (Tournier et al., 2020).

ICCG (An engineered variant of LCC with four mutations F243I/D238C/S283C/Y127G) reached a yield of 70.1 grams of terephthalic acid (TA) per liter per hour. A 150 liter pilot using ICCG was conducted to evaluate industrial feasibility, showing that enzyme costs represented only about 4% of the price of virgin PET. Additionally, high-purity terephthalic acid (99.8%) was recovered through standard purification methods, also recycling of 100,000 tons of PET per year will produce around 60,000 tons of sodium sulfate (byproduct) per year, representing 0.28% of the world market of sodium sulfate, This amount of this byproduct generated is manageable and commercially viable (Tournier et al., 2020).

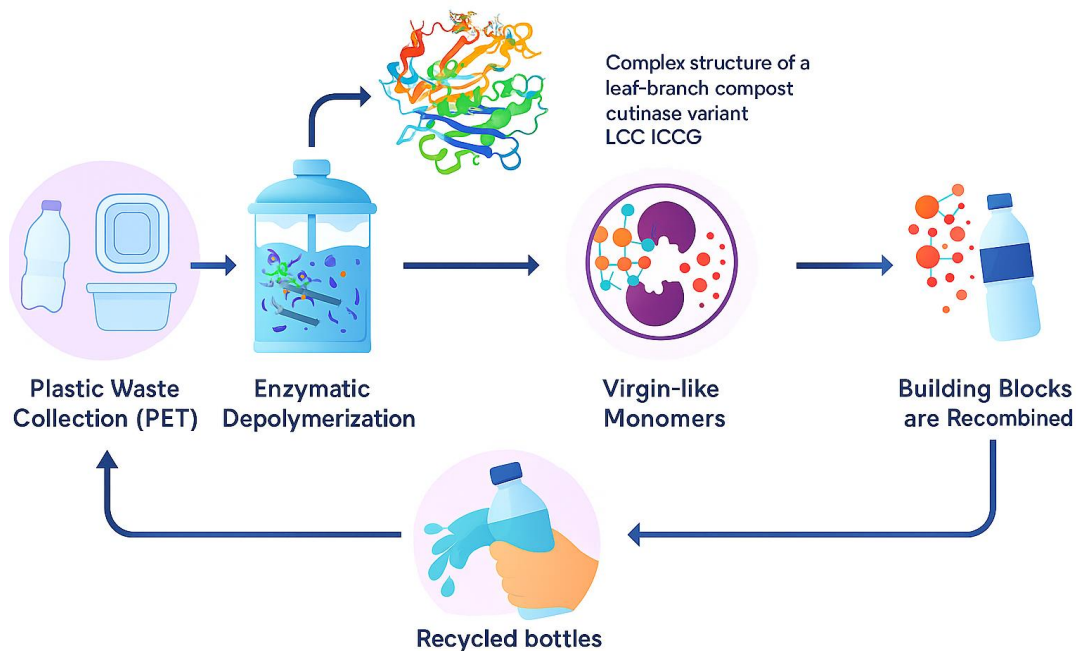


Figure 4: Schematic illustration of the sustainable degradation of PET using the LCC-ICCG enzyme (Complex Structure of a Leaf-Branch Compost Cutinase Variant LCC ICCG_RIP, 2022, Carbios - Innovating for a True Circular Economy in Plastics, 2025.)

Although its scientific advancements are revolutionary, the company, like many others in the environmental biotechnology sector, has logistical and operational difficulties that may be significantly alleviated using digital transformation tools. Among these tools, BCT is a compelling solution to enhance transparency, traceability, and efficiency across Carbios' plastic recycling value chain (El-Rayes et al., 2023).

One of the foundational challenges in Carbios' operations is ensuring the quality and sustainability of plastic waste input. Post-consumer PET plastic, the raw material, is frequently gathered from various sources, such as consumer waste streams, industry suppliers, and municipal recycling facilities. It is challenging to confirm the waste's provenance, state, and sustainability, particularly when it passes through several different channels. Blockchain can address this issue by creating a tamper-proof, time-stamped digital ledger that tracks plastic waste from its point of collection all the way to Carbios' processing facility. Each batch of PET waste could be recorded on-chain with a unique identifier, linked to metadata such as collection location, collection date, weight, contamination level, and certifying authority. This ensures only verified and traceable waste enters

the enzymatic recycling process, improving input quality and strengthening Carbios' environmental claims.

Otherwise, the supply chain for Carbios is naturally complicated, with many parties involved, including garbage collectors, shipping firms, operators of recycling facilities, quality control laboratories, and ultimately, the manufacturers and retailers who use the recycled plastic. This complexity frequently results in inefficiencies, inconsistent data, and a lack of chain-wide visibility in the absence of a single system. To optimize its supply chain coordination, Carbios adopted BCT because it provides a decentralized yet synchronized platform where all authorized stakeholders can record and access information in real time.

Smart contracts, programmable agreements on the blockchain, can automate key transactions, such as releasing payments once a shipment is delivered or once quality metrics are confirmed. This automation minimizes human error and eliminates the need for trust among parties, as the blockchain ledger guarantees data integrity and execution of predefined rules (Sanwar Hosen et al., 2020).

BCT provides an ideal infrastructure to support Carbios' mission as presented in Table 1 and Figure 5. From sourcing and supply chain management to environmental reporting and customer involvement, it answers fundamental operational problems. Although most of Carbios' attention is still on its biological technologies, BCT will significantly improve its recycling programs' effect, scalability and dependability.

This biotechnology and blockchain combination is a promising new area of sustainable innovation that can be used as a template by other businesses looking to build a more sustainable and responsible future (Taylor et al., 2020).

Table 1. The steps of the Blockchain based plastic waste tracking at Carbios (Carbios - Innovating for a True Circular Economy in Plastics, Retrieved September 28, 2025).

Step	Actors/Actions	Blockchain role
Plastic waste collection	Actors: Households, businesses, recycling centers, municipalities. Action: Collection and initial source-separation of PET plastic, with documentation of key metadata	Post-consumer PET plastic is gathered and sorted at the source, with key information such as the collection date, geographic location, and collector identification

	such as collection date, geographic location, and collector identification	systematically recorded, each collection event is immutably recorded on the blockchain as a dedicated transaction.
Identification and tagging	Each batch of collected PET waste is assigned a unique digital identifier containing metadata such as origin, weight, polymer type, and sustainability certifications.	Blockchain immutably links all recorded attributes to the batch's digital identity, enabling reliable tracking and preventing substitution or fraud. Records all data linking identity to each batch.
Transportation tracking	Transport to Carbios or intermediaries (GPS tracking, IoT sensors for location and environment)	Real-time, tamper-proof logging of route, checkpoints, and delivery.
Quality inspection and verification	Actors: Lab technicians, automated systems. Action: Incoming plastic waste is analyzed for purity, contamination, and suitability for enzymatic recycling.	Records inspection results immutably (Test results, batch linking), triggers smart contracts.
Arrival at Carbios facility	Waste officially enters the enzymatic recycling facility (Verified entry timestamp).	Confirms intake and closes traceability loop.
Final processing confirmation	Action: Depolymerization into reusable monomers (efficiency, energy use, emissions, yield).	Final confirmation entry, updates on environmental impact stats on-chain.
Ledger access for stakeholders	Users: Consumers, brands, regulators, auditors. Function: Audit and trace waste life cycle (Blockchain dashboard, QR scan access).	Ensures transparency, builds trust, supports ESG reporting.

From Figure 5 it is also possible to visualize the different steps of implementing BCT where each block is linked to a hash, it is like a digital fingerprint or unique ID for a block of data, and each block builds on the previous one, increasing the transparency, traceability, and added value of information along the chain.

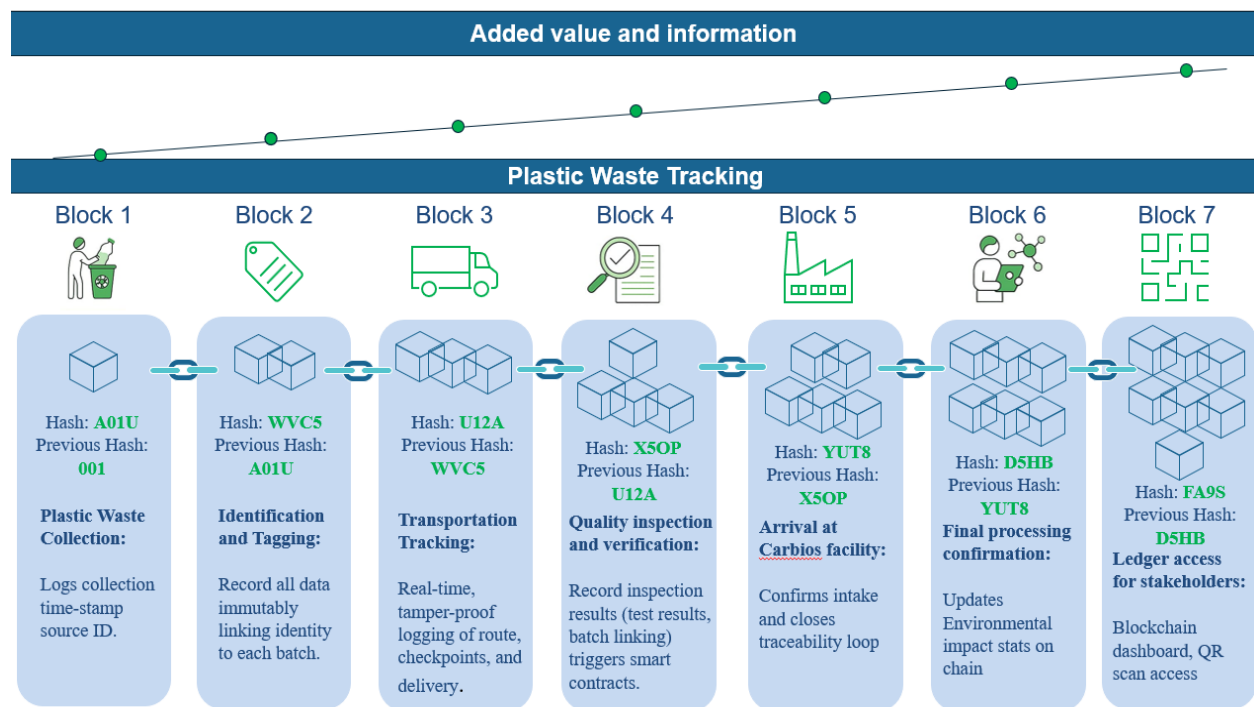


Figure 5: Representation of the blockchain blocks with increasing information about Carbios’s plastic waste tracking process (Carbios - Innovating for a True Circular Economy in Plastics, Retrieved September 28, 2025).

- **Challenges and Limitations of Implementing Blockchain Technology**

Although BCT presents encouraging ways to improve efficiency and transparency in plastic recycling procedures, its adoption is challenging. As a leader in enzymatic plastic recycling, Carbios may encounter several challenges when incorporating BCT into its business processes.

- **Regulatory Uncertainty**

Uncertainty in regulations is a significant obstacle Carbios may encounter when implementing blockchain technology. Since BCT is still in its infancy, many nations and regulatory agencies have not yet developed thorough frameworks or policies for its application, especially in fields like waste management and environmental biotechnology. Companies may face legal ambiguity and compliance concerns because of the absence of clear, uniform regulations. Because they might not know which laws apply or how to meet changing compliance standards, Carbios may find that navigating these murky regulatory landscapes slows the adoption process or increases operational risks (Aich et al., 2019).

➤ **Scalability Issues**

Another significant issue Carbios may run into when incorporating BCT is scalability. Because of their consensus and data verification procedures, blockchain networks, especially public ones, may find it difficult to rapidly handle high transaction volumes. Scalability issues could cause delays and inefficiencies in the Carbios supply chain, where enormous volumes of data must be documented and updated almost instantly, from collecting events to quality checks and transportation logs. These restrictions can make it more difficult for the system to deliver precise and timely traceability data, essential for upholding stakeholders' trust and fulfilling environmental compliance requirements. Furthermore, scaling blockchain solutions without sacrificing decentralization or security is still a difficult technical task that calls for cautious platform selection and the potential application of layer-two or hybrid methodologies. To guarantee that the blockchain system can manage operational needs as the business expands and the volume of plastic processed rises, Carbios must address scalability (Aich et al., 2019).

➤ **Technological Complexity**

Carbios may encounter difficulties implementing BCT because of its considerable technological complexity. Among other specialized talents, blockchain systems necessitate a thorough understanding of distributed ledger structures, cryptographic security, and innovative contract development. Developing or obtaining this technical knowledge can be outside the purview of a business specializing in biotechnology and enzymatic recycling. Additionally, it is more difficult to find competent workers to properly design, deploy, and manage blockchain solutions due to the global shortage of blockchain expertise. In addition to raising expenses and causing inferior system performance or vulnerabilities, this skills gap can cause project timeline delays (Nagariya et al., 2022).

1.5.2 "Thank My Farmer" App: Adoption of BCT in Agri-food Biotechnology

The agri-food industry has been under growing pressure to improve sustainability, traceability, and transparency in recent years. A unique answer to these problems is provided by blockchain technology, which is distinguished by its decentralized and unchangeable ledger structure. This case study examines the **"Thank My Farmer"** mobile application launched in early 2020, developed by Farmer Connect, built on IBM's Blockchain (Hyperledger Fabric), as a real-world example of blockchain adoption in the context of agriculture and food biotechnology specifically within the coffee supply chain (ThankMyFarmer, 2025).

Farmer Connect applies blockchain technology to make the coffee supply chain more transparent and people-centered by digitally connecting farmers directly with brands and consumers. Using IBM Blockchain built on Hyperledger Fabric, each step of the coffee value chain is securely recorded on a shared ledger, from cultivation at the farm to export, roasting, and final retail distribution. Every transaction is time-stamped, verified by authorized participants, and stored in a tamper-resistant manner, ensuring that supply chain data remains trustworthy and traceable throughout the product’s journey. This blockchain infrastructure enables different stakeholders, farmers, exporters, roasters, and retailers, to share a single reliable source of information without relying on a central authority. Smart contracts automate data validation and access permissions, ensuring that only authorized actors can add or view sensitive information, while maintaining overall transparency (Farmer Connect: Trusted Data for EUDR Compliance & Reporting, 2020).

The consumer-facing “Thank My Farmer” application translates this technical infrastructure into an accessible and engaging experience. By scanning a QR code on the coffee package, consumers can trace the origin of their product and learn about the people and processes behind it (figure 6). The app provides verified information such as the farm’s geographic location, key milestones along the supply chain, certification status (organic or fair trade), and a visual map of the coffee’s journey. In some cases, consumers can even contribute directly to sustainability initiatives supporting the farming communities (Trollman et al., 2022).

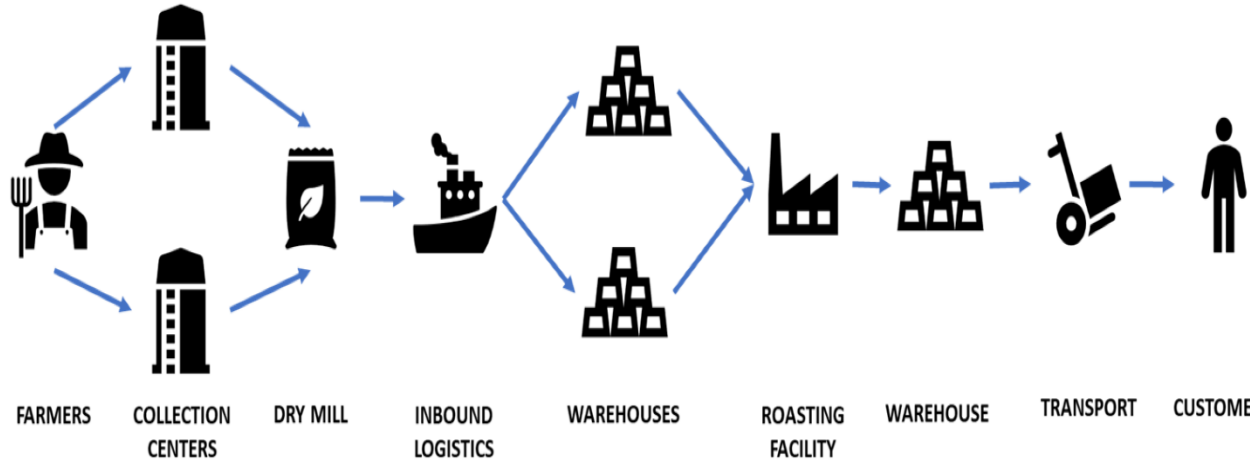


Figure 6: Visualization of the Folgers coffee supply chain provided by the application, Thank My Farmer (Trollman et al., 2022)

- **Blockchain Implementation and Supply Chain Integration**

Farmer Connect’s blockchain implementation is built on Hyperledger Fabric, a modular and enterprise-grade distributed ledger platform developed by the Linux Foundation and supported by IBM. This permissioned blockchain framework incorporates key features such as private channels for confidential transactions, endorsement policies that validate transactions based on pre-defined rules, and smart contracts that automate processes like origin verification, certification validation, and logistics data tracking. The system enables active participation from multiple stakeholders across the supply chain, including farmers (who input harvest and certification data), cooperatives (who log quality and logistics information), roasters (who verify origin and roasting processes), retailers (who assign traceability data to product), exporters (who manage shipping records) and consumers (who access this verified data through QR codes) as shows Figure 7.

The "Thank My Farmer" app from Farmer Connect is a prime example of how blockchain might revolutionize agri-food biotechnology by fusing decentralized traceability, ethical consumer involvement, and digital transparency. It provides a strong argument for further adoption in other biotechnology-related fields where safety, ethics, and traceability are crucial, like crop genomics, cattle health, and sustainable aquaculture.

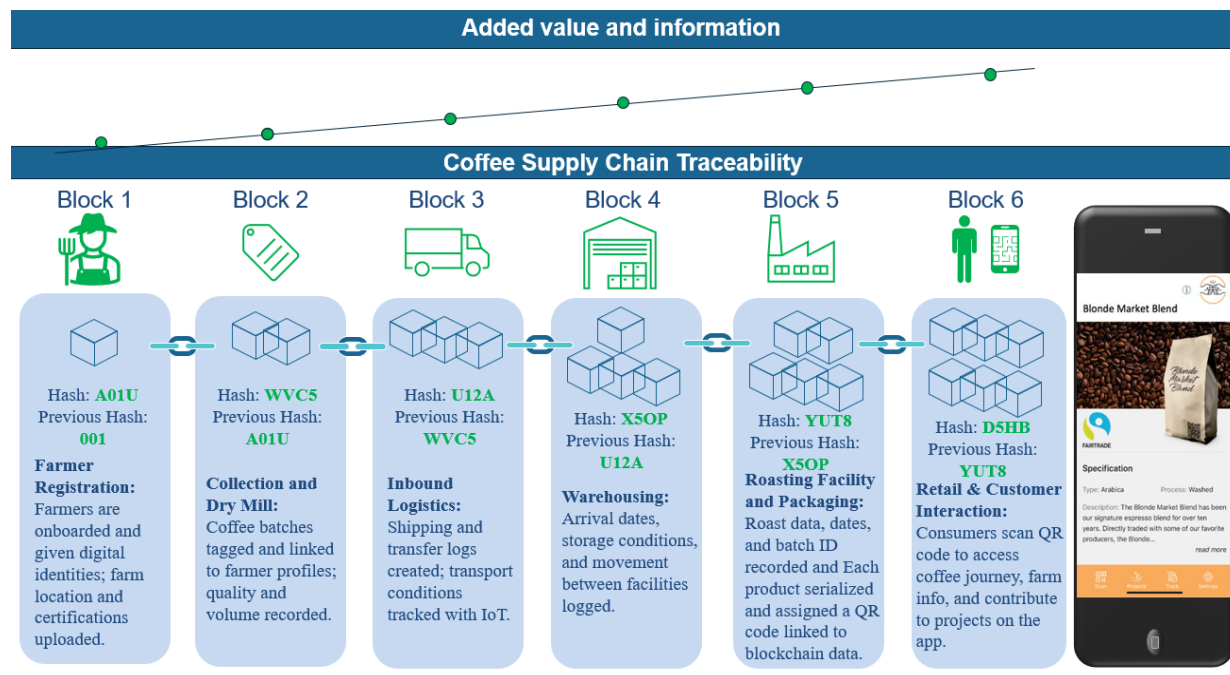


Figure 7: Representation of the blockchain blocks with increasing information of Thank My Farmer coffee supply chain traceability.

- **Challenges and Limitations in Blockchain Implementation in Agri-food Supply Chains**

According to Bager et al, BCT has been the subject of hype and is frequently presented as a universally applicable solution to intricate issues in agri-food supply chains. Many supporters think blockchain can guarantee sustainability and transparency in the coffee production process, from farm to cup. The writers warn against oversimplified tales, nevertheless. They contend that digital traceability alone cannot address systemic problems like poverty, inequality, and poor governance (Bager et al., 2022).

- **Data Reliability and Trust**

The immutability of blockchain technology, the inability to change data after it has been entered, is one of its main selling points. This strength, meanwhile, is also a significant drawback. The accuracy of the data being submitted cannot be ensured by the technology. Information regarding farming methods, environmental compliance, or working conditions is frequently self-reported or supplied by intermediaries in agri-food supply chains, especially in smallholder contexts. Instead, then identifying or fixing inaccurate or misleading data, blockchain will maintain and validate it. Since the chain is only as reliable as its weakest link, this poses a severe constraint. The transparency provided by BCT may be more surface level than meaningful in the absence of strong third-party verification (Bager et al., 2022).

- **Implementation and Maintenance Costs**

Implementing blockchain is not a trivial matter, it involves significant upfront investments in technology, training, certification, and sometimes new hardware for data collection and entry. These expenses may be unaffordable for those who are already making a living on low margins, such as smallholder coffee growers (Bager et al., 2022).

Based on the study of Hossein Havaeji about Cost Optimization of Blockchain-enabled Supply Chain System (2023), Implementation and maintenance costs splits into two main categories:

Blockchain installation costs: encompass the one-time and periodic investments required to establish and maintain a functional system. Typically, fixed costs range from about \$860 to \$1,160 annually and include expenses for server setup, software licenses, and hardware. Onboarding fees typically range from \$180 to \$260 per company and include training participants, such as suppliers to integrate into the network. Annual maintenance and monitoring costs, which are expected to be

between 15 and 25 percent of the project's total value, are required to guarantee the system functions effectively after these initial expenses. Together, these elements draw attention to the significant initial and ongoing financial outlays involved in putting in place a blockchain infrastructure (Havaeji, 2023)

Blockchain transaction costs: often considered operating expenses, encompass the day-to-day expenditures incurred each time the system is used, equivalent to utility bills. Depending on network activity and gas pricing, these expenses might range from about \$1 to \$4 per transaction or up to \$40 per day. Gas fees are necessary for validating and recording transactions on networks like Ethereum or Hyperledger. Additionally, when data is kept off chain, like in the case of supply chain records or patient records stored on cloud platforms like IBM Cloud, storage fees are incurred. These prices typically range from \$300,000 to \$700,000 per year for 180 to 420 terabytes of data (Havaeji, 2023)

According to the MediLedger DSCSA Pilot Project report, Infrastructure, storage, and node operation costs are the three main components of the cost of integrating BCT into the pharmaceutical supply chain. Hardware expenses were projected to be about \$4,000 for 100 TB and \$16,000 for 400 TB, based on storage requirements of about 399 TB over seven years without pruning or 111.8 TB with pruning. It was estimated that the total pharmaceutical industry's annual node operation costs would range from \$5 to \$10 million. The study concluded that processing and storage expenses can be controlled, especially when using a consortium-based governance model that divides costs among interested parties. Though economies of scale and efficiency advantages allow large manufacturers and distributors to overcome these costs, smaller firms bear disproportionately greater financial constraints, which could make adoption difficult (DSCSA Pilot Project Program | FDA, 2024).

➤ **Limited Impact on Actual Sustainability Outcomes**

Bager et al, concludes by raising doubts about whether blockchain genuinely promotes sustainability advancements or merely gives the appearance of action. Blockchain does not enforce claims on environmental compliance or ethical sourcing, but it can assist in tracking them. Businesses run the risk of engaging in digital greenwashing when they employ BCT to show consumers that they are responsible without actually implementing significant improvements. Furthermore, the advantages of blockchain will mainly stay symbolic if the underlying reasons of

unsustainable practices, such as low farm-gate prices, insecure land tenure, or inadequate institutional oversight, are not addressed. The authors contend that the promise of BCT shouldn't overshadow the necessity of robust governance and systemic change (Bager et al., 2022).

1.5.3 Merck & Co.: Leveraging Blockchain for Pharmaceutical Traceability and Anti-Counterfeiting

Merck, a multinational biopharmaceutical company, recognized early the potential of blockchain as a tool for regulatory compliance under the United States' Drug Supply Chain Security Act (DSCSA) and strategic innovation in product integrity management. By participating in the U.S. Food and Drug Administration's (FDA) blockchain pilot program, Merck explored a decentralized and transparent approach to pharmaceutical traceability, collaborating with industry and technology leaders to build a robust system for tracking drug products from production to point-of-dispense (DSCSA Pilot Project Program | FDA, 2024) .

In response to the regulatory and ethical imperatives of securing the drug supply chain, Merck participated in a U.S. FDA pilot program to evaluate the use of BCT in meeting DSCSA compliance requirements.

The pilot involved:

- Serializing individual pharmaceutical units involves assigning a unique digital identity to each package.
- Integrating these identities into a blockchain-based ledger enables immutable, real-time tracking across the supply chain.
- Partnership with other industry stakeholders and blockchain consortia, such as MediLedger, which provided the technical framework for interoperability and data integrity.

Merck's strategy was collaborative and forward-looking, incorporating blockchain as a central enabler of secure and transparent drug tracking (DSCSA Pilot Project Program | FDA, 2024).

- **Consortium-Based Collaboration**

Merck joined forces with IBM, KPMG, and Walmart to form a consortium in the FDA's pilot program. Each organization brought specific expertise. Merck contributed pharmaceutical manufacturing and regulatory knowledge. IBM supplied its enterprise blockchain platform, based on Hyperledger Fabric, a permissioned blockchain protocol. KPMG offered auditing, compliance, and integration services. Walmart, a large-scale distributor and retailer, provided end-user retail insights and infrastructure (IBM, KPMG, Merck and Walmart to Collaborate as Part of FDA's Program to Evaluate the Use of Blockchain to Protect Pharmaceutical Product Integrity - Merck.Com, 2019).

This cross-sector collaboration ensured that the blockchain solution addressed the full spectrum of supply chain needs from production to retail (Chien et al., 2020).

- **Blockchain Infrastructure and Technical Architecture**

The system architecture used Hyperledger Fabric, a permissioned, modular BCT that enables safe, private business transactions. Among the implementation's salient aspects were (Chien et al., 2020):

- **Node Network:** Several nodes, each keeping a synchronized copy of the ledger, represented various stakeholders, including manufacturers, distributors, wholesalers, and pharmacies.
- **Smart Contracts (Chaincode):** Transactions like drug shipments, receipt confirmations, and ownership transfers can now be automatically validated thanks to the codification of business processes into smart contracts.
- **Data Integrity:** An unchangeable record of every movement and interaction with the medication package was produced by cryptographically signing and timestamping each transaction.
- **Private Channels:** Only authorized parties were given access to sensitive information, such as prices or company-specific operations, protecting privacy and guaranteeing compliance.

Building on this robust blockchain infrastructure, the next critical layer of the system concerns how individual pharmaceutical products are uniquely identified and tracked throughout the supply chain.

- **Serialization and Digital Identity**

A key component of the approach is product serialization, which DSCSA requires. A distinct serial number associated with a digital identity was given to every medication unit. The blockchain included a record of this identity, which could be used to check the product's manufacturing information and origin, verify the product's authenticity at any stage of the supply chain, and look for irregularities or illegal attempts to change or redirect the product (IBM, KPMG, Merck and Walmart to Collaborate as Part of FDA's Program to Evaluate the Use of Blockchain to Protect Pharmaceutical Product Integrity - Merck.Com, 2019).

- **Interoperability and Scalability**

The pilot also tackled interoperability, a significant issue in pharmaceutical supply chains. The blockchain solution may be able to interface with industrial legacy systems using open standards and application programming interfaces (APIs). As a result, Merck's blockchain platform was guaranteed to be scalable and work with partners that might not have embraced BCT yet. Additionally, the system's capacity to expand across many stakeholders, confirm product movement in almost real-time, and preserve ledger consistency across all nodes was proven by real-world testing conducted throughout the trial (IBM, KPMG, Merck and Walmart to Collaborate as Part of FDA's Program to Evaluate the Use of Blockchain to Protect Pharmaceutical Product Integrity - Merck.Com, 2019).

- **Drug Traceability Flow with Hyperledger Fabric**

This section explains how the execute-order-validate transaction processing approach, which is common for Hyperledger Fabric, is used to carry out and communicate transactions in the pharmaceutical supply chain across various stakeholders. Figure 8 illustrates this. This architecture provides a detailed description of the stages involved in completing a transaction processing cycle. An organizational user (client app) from a registered company, like a manufacturer or supplier, first submits a transaction proposal in the suggested Hyperledger Fabric architecture. To read and/or update the ledger, the transaction proposal requests that a chaincode function be invoked with specific parameters. According to the chaincode endorsement policy, this proposal is sent to each endorsing peer. To be clear, each chaincode has an endorsement policy that specifies which

companies, and to a lesser extent, whose peers, are required to sign or verify each transaction for that code. The client's cryptographic credentials (obtained from the membership service provider (MSP)), the transaction payload, which includes the name of the chaincode function to be performed with input arguments, the channel and chaincode IDs, and other factors make up the transaction proposal. To obtain agreement that the transaction is legitimate, the client app forwards this proposition to a group of endorsing peers. The proposal phase is the name given to this stage (Uddin et al., 2021).

According to the chaincode's endorsement policy, a certain number of endorsing peers execute the transaction proposal. In response to the submitted transaction proposal, these outcomes (also known as endorsements) will be encrypted, recorded, and delivered back to the client app together with the cryptographic signatures and RW (read-set and write-set) sets of endorsing peers. It should be noted that the client app keeps gathering endorsements until it complies with the chaincode endorsement rules. The ledger is not updated currently. The endorsement phase is the name given to this stage (Uddin et al., 2021).

After receiving enough endorsement responses, the client app checks them to see if the RW sets match, ensuring that the chaincode ledger was not modified between the proposal and endorsement stages. The transaction proposal and responses are then put together by the client app and sent to the Ordering Service (OS) as a transaction message. The transaction with RW sets, peer signatures, and channel identifier are all included in this message. The decentralized Ordering Service determines the execution order of each channel's submitted transactions using a pluggable consensus system. 34 Multiple drug transactions are arranged chronologically into blocks by the ordering service, which links the hashes of the blocks to those of earlier blocks. We refer to this stage as the ordering step (Uddin et al., 2021).

The execution phase is the last stage. It involves the OS broadcasting the freshly generated blocks to the Hyperledger Fabric network's top peers. Using the gossip protocol, the leading peers are then responsible for sharing the blocks with other committing peers inside the organization. The Ordering Service is aware of the leading peers who are chosen by each organization. Peers confirm that the RW sets have not been violated since the last check and determine whether the endorsements are legitimate in accordance with the chaincodes' endorsement policies. The transaction is flagged as invalid if any endorsement is deemed invalid or if the RW settings do not

correspond to the current world state. Determinism is ensured by updating the ledger and having all peers append the transactions to the channels' ledgers in the specified order. The world state will be updated by legitimate transactions. The global state is not updated by invalid ones, but they are kept in the ledger. Lastly, each peer in the network will notify the client app that submitted the transaction proposal of the transaction's success (Uddin et al., 2021).

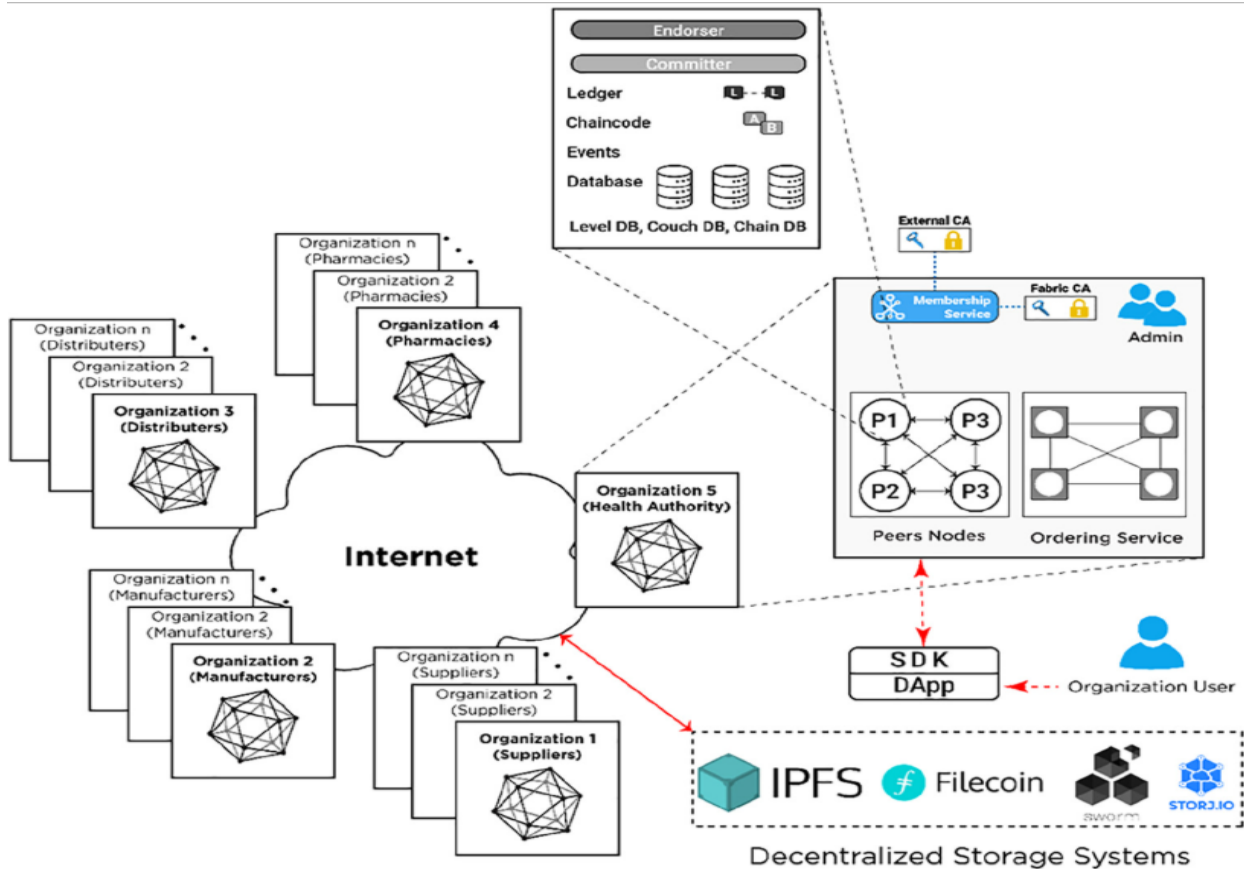


Figure 8: Hyperledger Fabric blockchain architecture (Uddin et al., 2021).

This example shows how blockchain can be a fundamental component of biotechnology, especially in fields where patient safety, product integrity, and traceability are critical, it holds a ton of potential, but it comes with a complex set of challenges and limitations. We will break it down into the key areas they'd be dealing with:

- **Challenges and Constraints in Implementing Blockchain Technology**
 - **Data Standardization Across the Supply Chain**

A primary obstacle that Merck & Co. would have when integrating BCT for pharmaceutical traceability is guaranteeing data uniformity throughout its extensive and intricate supply chain.

Because so many parties are involved, from distributors and retail pharmacies to suppliers of raw materials, data is frequently gathered and structured in various ways. For blockchain to function effectively, structured and interoperable data is a prerequisite. The blockchain loses its dependability if these stakeholders disagree on serialization standards or data input formats. The promise of complete traceability is broken, and counterfeit detection is much less successful in the absence of this consistency (W. Akram et al., 2024).

➤ **Integration with Legacy Systems**

Merck already makes use of well-known enterprise systems including enterprise resource planning (ERPs), warehouse management systems, and serialization software, just like most pharmaceutical giants. It's no easy task to incorporate BCT into this current digital architecture. Since these systems weren't designed with blockchain in mind, middleware development and customization would frequently be required, which would be expensive and technically hard. Additionally, there is a chance that implementation will interfere with current operations. This interruption might be a major worry for a business that depends on prompt delivery and high-quality products (W. Akram et al., 2024).

➤ **Scalability and Performance**

Every day, a big pharmaceutical company like Merck handles millions of transactions, from batch-level data management to tracking individual pill bottles. Blockchain systems may find it challenging to handle such volume, particularly public or hybrid blockchains. Real-time drug authenticity verification is not feasible if transaction rates are too sluggish or if network congestion becomes a problem. The blockchain must develop to manage high-throughput performance without sacrificing speed or security as the sector expands digital traceability (W. Akram et al., 2024).

➤ **Data Privacy and Confidentiality**

Transparency is one of blockchain's advantages, however not all data should be publicly disclosed in the pharmaceutical industry. Pricing information, unique formulae, and patient data are all extremely sensitive. For Merck, putting blockchain into practice necessitates striking a delicate balance between data privacy and visibility for traceability, particularly considering laws like GDPR in Europe and HIPAA in the US. In a distributed system, when more parties have access to the ledger, this balancing act is very difficult (Uddin et al., 2021).

➤ **Governance and Control**

Who manages the rules of the blockchain network? Who decides who can join or what data is recorded?. Particularly with consortia-based blockchains, where several rivals use the same network, these governance issues are crucial. Any blockchain governance model in which Merck takes part would have to be equitable, safe, and impervious to manipulation. Stakeholders might be hesitant to invest in the system's maintenance or trust it if there is weak, opaque governance, which could restrict effect and delay adoption (Uddin et al., 2021).

1.5.4 JBS: The Transparent Livestock Farming Platform (Green Platform)

JBS S.A. is the world's largest meat processing company, headquartered in Brazil, and a major supplier of beef, pork, and poultry globally (JBS ESG, 2020). People have long been worried about how Brazil's beef business affects the environment, especially because of the illegal cutting down of trees in the Amazon that is linked to cattle ranching. JBS required a strong, unchangeable, and transparent supply chain monitoring system to handle mounting pressure from global stakeholders, environmental groups, and customers. Presenting blockchain technology, which is perfect for data integrity, traceability, and decentralized trust (Salman Abdou & El-Mahdy, 2024).

- **Goals of the Platform: The Livestock Farming Platform**

Eliminating illegal deforestation within the beef supply chain is a crucial step toward a more ethical and environmentally responsible livestock industry. Extending traceability beyond direct suppliers to include indirect ones, where the risk of deforestation is frequently highest, is essential to genuinely address the core of the issue. In addition to increasing accountability, enhancing openness and compliance along the whole livestock chain will foster trust in the industry. Meeting global sustainability goals, like reaching net-zero targets and preserving our world for coming generations, depends on these initiatives (JBS ESG, 2020).

- **Technological Infrastructure**

JBS built a blockchain-based platform using geospatial data, satellite monitoring, and artificial intelligence (AI) to collect, analyze, and store supply chain data. This is how it operates:

Ranchers enter their farm and cattle batch information into the portal to start the supplier registration procedure. Technology maps these areas for accurate monitoring using cadastral data and geo-referenced agricultural borders. Data collection is crucial, as JBS collects essential data

from satellite providers and Brazilian government registries like CAR and GTA. Records of land ownership, cattle movement histories, and deforestation alarms from PRODES and MapBiomas are some examples of this data. Every transaction, including the transfer of cattle, is permanently documented on the blockchain to guarantee transparency and integrity. Before approving the data, smart contracts automatically confirm that specific requirements are fulfilled, such the lack of deforestation alarms. Crucially, JBS is unable to alter historical records, which strengthens accountability and permits exhaustive audits. Lastly, a compliance dashboard that identifies farms that are not in compliance is used to do a supplier risk analysis. After that, high-risk providers are either eliminated from the supply chain completely or hired to enhance procedures (Transparent Livestock Farming Platform Launches | JBS Global UK, 2021).

The JBS Green Platform (Figure 9) leverages BCT to enhance traceability and ensure a deforestation-free beef supply chain. The process begins when JBS authorizes access to GTA (Animal Transit Guide) data related to its direct suppliers (Step 1). A survey is then conducted to identify the suppliers behind those direct suppliers (Step 2), and this information is retrieved and stored on the blockchain (Step 3). The monitoring system analyzes this data (Step 4), cross-referencing it with geospatial analysis, the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) list of embargoed areas, and blacklists for labor violations to identify any non-compliant upstream suppliers (Step 5). The blockchain platform then records these findings (Step 6), helping direct suppliers only source cattle from compliant farms (Step 7). Finally, JBS receives GTAs from verified suppliers, ensuring a deforestation-free supply chain (Step 8). This interconnected system not only provides transparency but also supports compliance with sustainability standards through immutable records and comprehensive risk assessment (JBS ESG, 2020).

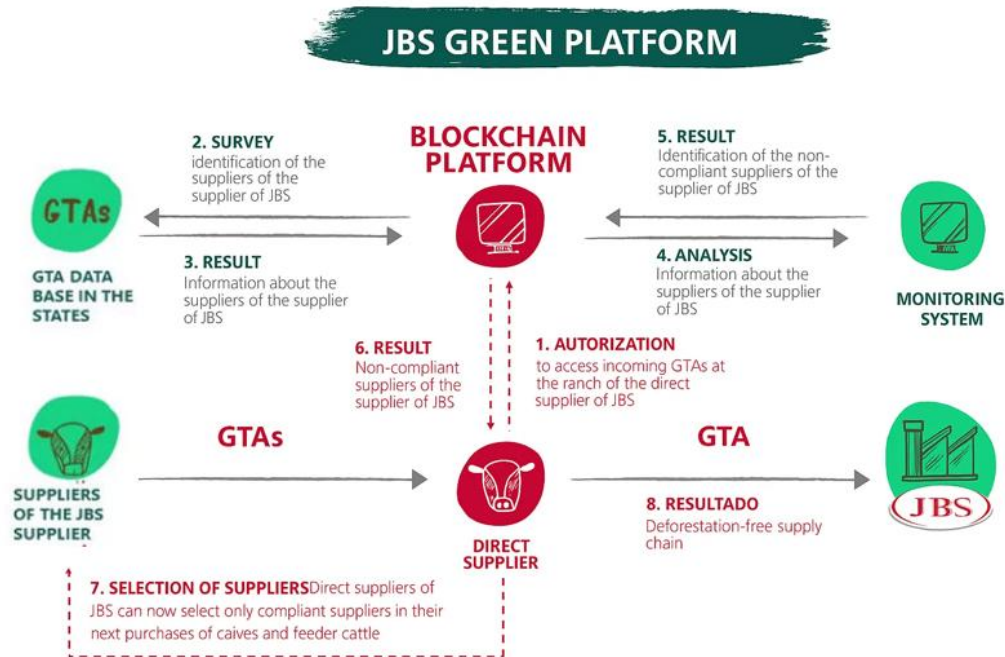


Figure 9: JBS Green Platform (JBS ESG, 2020)

- **Impact of Using Blockchain Technology**

By enabling retailers and consumers to track beef down to the farms where it was produced, this approach significantly improves transparency and promotes more trust and well-informed decision-making. By actively removing suppliers connected to unlawful deforestation, it also plays a critical role in protecting the environment by making sure that only sources that comply with regulations stay in the supply chain. The platform generates audit-friendly data that third parties may trust because all transactions are permanently documented. All these characteristics contribute to the development of international trust and encourage adherence to new supply chain laws that prohibit deforestation in places like the US and the EU (Transparent Livestock Farming Platform Launches | JBS Global UK, 2021).

- **Challenges and Limitations of the Livestock Farming Platform**

Even with the creative use of blockchain technology, JBS still has several significant obstacles to overcome before its supply chain is completely secure. The difficulty of identifying indirect suppliers is one of the main obstacles, in Brazil, cattle frequently go through several farms before being killed, and many of these middlemen aren't officially registered, which results in data blind spots. Because some farms are in embargoed parts of the Amazon or operate without legal titles,

land tenure issues further complicate matters and limit the usefulness of blockchain when the underlying data is inaccurate. There are additional obstacles to adoption among smaller ranchers, who can consider digital technology to be burdensome or superfluous, particularly in areas with inadequate internet infrastructure and access. Lastly, the system mostly relies on voluntary compliance without substantial government support, which can limit its overall impact (Jackson, 2023).

JBS's blockchain platform is a revolutionary attempt to produce beef in a sustainable manner. It creates a model for addressing deforestation through accountability by fusing supply chain reform with innovative technology. Despite the complexity of the path to complete traceability, JBS has set the foundation with open, verifiable, and expandable procedures. Blockchain integration in the food business may go from being an innovation to a need as climate restrictions tighten, particularly in North America and Europe.

1.5.5 Medicalchain: The Implementation of Blockchain in Medical Biotechnology

Electronic health records, or EHRs, have become essential to contemporary medical practice as the healthcare sector moves toward digital transformation. However, problems including data silos, lack of interoperability, restricted patient management also traditional EHR systems are prone to frequent security breaches.

Medicalchain, a UK-based health tech business, responded to these issues by launching a blockchain-powered solution that improves security, decentralizes patient data governance, and enables clear and effective data interchange (Zhou et al., 2024).

- **Implementation Strategy**

The implementation of Medicalchain's system is a multifaceted approach that marries cutting-edge blockchain architecture with practical healthcare workflows. The dual blockchain paradigm is at the heart of the project's architecture. Medicalchain manages digital identities, logs access transactions, and runs smart contracts using Ethereum as its public-facing blockchain layer, ensuring that all actions pertaining to patient data are transparent and unbreakable. Hyperledger Fabric, a private permissioned blockchain, is integrated into Medicalchain concurrently to store references to encrypted medical records and implement access control measures. The advantages of private data protection and public auditability are successfully combined in this hybrid paradigm, which is crucial when managing sensitive health data (Zhou et al., 2024).

The use of smart contracts, which are designed to impose access control on patient health data, is a key component of Medicalchain's approach. When a healthcare provider requests access to a patient's records, the smart contract determines if the provider is authorized based on the patient's prior approvals. Patients can have fine-grained control over their data using these permissions, which might be time-bound and purpose-specific. By eliminating the requirement for a central authority to arbitrate data sharing, this decentralized approach lowers administrative costs and lowers the possibility of data breaches or single points of failure (Zhou et al., 2024).

By introducing MedTokens, which are digital tokens that comply with Ethereum Request for Comment 20 (ERC20), Medicalchain has integrated a tokenized economy into its ecosystem in addition to its technical design. These tokens have several uses on the platform. Patients primarily utilize MedTokens as a digital key to grant third parties, such as researchers, insurers, and healthcare providers, access to their medical records. Second, Medicalchain's telemedicine platform, MyClinic.com, allows patients to schedule virtual consultations and pay doctors directly using tokens. This makes it easier for patients to pay for services. The use of MedTokens to reward patient involvement in research is arguably the most inventive. Tokens are used to reward patients who consent to share anonymized data with pharmaceutical or scientific research organizations. This creates a win-win data-sharing economy based on openness and consent (Zhou et al., 2024).

One useful interface for interacting with the blockchain infrastructure is the telemedicine portal MyClinic.com. Patients can make appointments, have video consultations with certified medical specialists, and safely share their medical history during sessions using this web and mobile application. Blockchain integration in this case guarantees that patient data is only accessible by authorized personnel, and all access logs are kept on file for auditing purposes. Furthermore, the Ethereum blockchain records all payment transactions, whether they are made with Fiat currency or MedTokens, guaranteeing transparency and lowering the number of billing disputes. In order to keep blockchain complexity under control and prevent non-technical users from adopting it, the platform was also designed with ease of use in mind (Zhou et al., 2024).

Medicalchain's pilot project with The Groves Medical Group in London was a notable component in its deployment. This project showed that integrating BCT into current clinical operations is feasible. Patients were asked to input their health information and create Medicalchain profiles throughout the experiment. They could then selectively allow access to certain elements of their

medical information and consult with doctors via MyClinic.com. The trial confirmed that blockchain may provide individuals complete control over their health information and improve data interoperability across providers. It also demonstrated that the model could function in practical situations without interfering with the provision of conventional healthcare (Zhou et al., 2024).

To illustrate the step-by-step strategy of the implementation of Medicalchain’s system, we refer to a visual model (Figure 10)

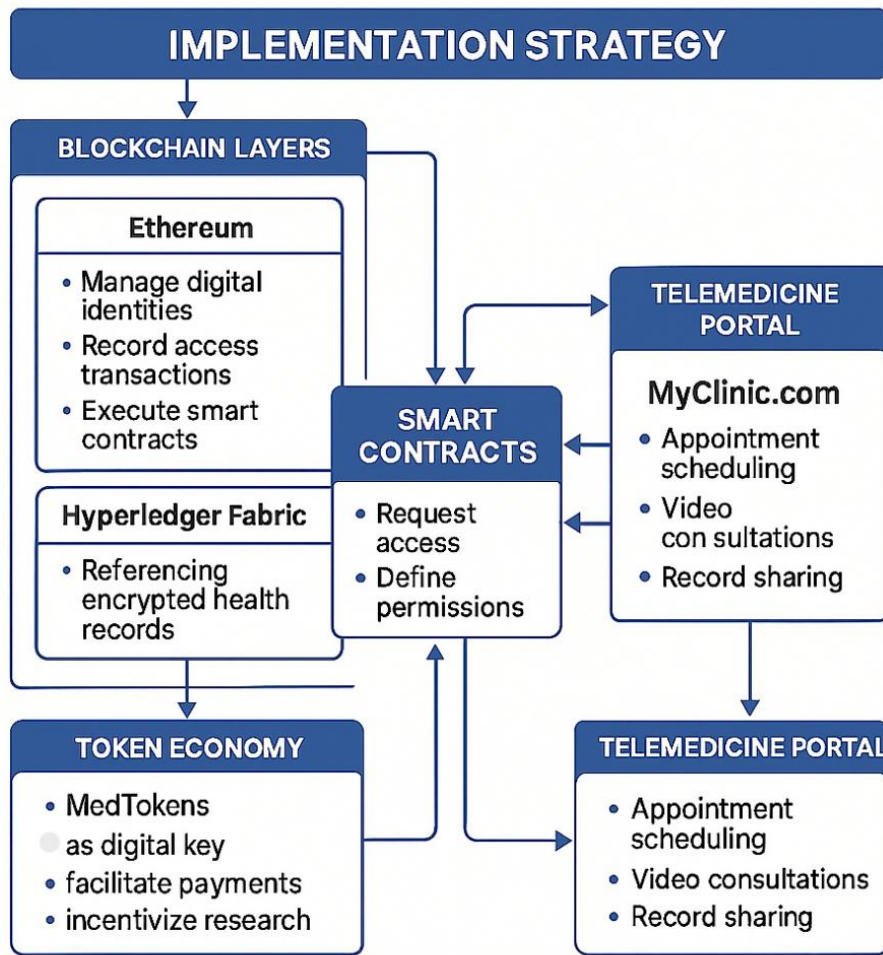


Figure 10: Medicalchain Implementation Strategy: A Blockchain-Driven Healthcare Ecosystem.

- **Technical and Adoption Challenges**

Adoption of blockchain in healthcare is fraught with implementation and technological challenges. Limited performance and scalability are major technological issues, blockchain networks frequently have high latency and low transaction throughput. Because of the constantly increasing amount of blockchain data, storage constraints also become a problem, leading to developments such as erasure coding and off-chain processing. Furthermore, there is still work to be done to modify blockchain systems to accommodate intricate relational queries and guarantee verified data integrity. Concerns about data security, especially adherence to laws like HIPAA (Health Insurance Portability and Accountability Act), make implementation more difficult from an adoption standpoint. Because there are no common standards, there are still issues with interoperability between various healthcare systems and blockchain platforms. Additionally, data ownership calls into question responsibility and access control, particularly in patient-centric models, underscoring the necessity of strong governance and frameworks for cross-institutional data exchange (Zhou et al., 2024).

The following table (Table 2) compares the chosen companies from our case studies, showcasing their types, their unique blockchain solution and their based country demonstrating the range of uses and tactical methods for utilizing blockchain technology.

Table 2. BCT implementation across industries: A comparative analysis of companies and their blockchain solutions.

Company Name	Type	Based Country	Blockchain Used	Reference
Carbios	Startup (Biochemistry company)	France	Private permissioned blockchain with smart contracts for supply chain management	(Carbios - Innovating for a True Circular Economy in Plastics, 2025)
Farmer Connect (Thank my Farmer)	Startup (Technology company)	Switzerland (headquarters)	IBM Blockchain (Hyperledger Fabric)	(ThankMyFarmer, 2025)
Merck & Co	Corporation (Pharmaceutical company)	Germany (headquarters)	Consortia-based blockchain for pharmaceutical supply chain	(W. Akram et al., 2024)

JBS S.A	Corporation (World's largest meat processing company)	Brazil		Private blockchain platform with smart contracts for the Green Platform/Livestock Farming Platform	(Transparent Livestock Farming Platform Launches JBS Global UK, 2021)
MedicalChain	Startup (Health tech company)	UK		Dual blockchain system - Ethereum (public) and Hyperledger Fabric (private)	(Zhou et al., 2024)
HyperLedger	Consortium (Open-source blockchain project)	USA (Linux Foundation)		Hyperledger Fabric (enterprise-grade distributed ledger platform)	(Trollman et al., 2022)
IBM	Corporation (Technology company)	USA		IBM Blockchain (based on Hyperledger Fabric)	(IBM.com, 2025)

2. MATERIAL AND METHODS

2.1 Questions Involved in the Present Research

Over the past decade, research on BCT has increased significantly, indicative of the growing complexity and breadth of blockchain applications. This growth is evidenced by the rise of different consensus algorithms designed to address specific challenges (Ahn et al., 2024).

To guide this bibliometric analysis, the following research questions, specifically tailored to focus on both theoretical development and practical implementation aspects of BCT will be considered (Kuzior et al., 2022) will be considered.

- RQ1: How have blockchain research publications evolved regarding volume and subject focus?
- RQ2: What are the key applications of BCT in the biotechnological sector?
- RQ3: What are the significant trends in blockchain technology, and how have they shifted over time?
- RQ4: How can blockchain be strategically modeled to support the integration of biotechnology supply chains and innovation ecosystems?

The research will be carried out in the database Scopus to expand the range of eligible documents from 2020 to 2025. Scopus was chosen because it covers a notable range of high-ranking journals and peer-reviewed articles of high quality. Table 3 provides the main steps for a bibliometric analysis (Passas, 2024).

Table 3. The main steps of a bibliometric analysis are as follows (Passas, 2024).

Step	Description	Tools/Software	Expected Outcome
Define Research Objectives	Clearly outline the objectives of the bibliometric analysis.	N/A	Clear research questions and objectives.
Literature Search and Data Collection	Collect relevant literature from Web of Science, Scopus, and Google Scholar databases or collect raw data (from no database) and build your own database.	EndNote, Mendeley, Zotero,	A comprehensive dataset of relevant publications.
Data Cleaning and Preprocessing	Clean and preprocess the data to ensure accuracy (removing duplicates and correcting author names).	R, Python, Excel or LibreOffice	A refined and accurate dataset ready for analysis.
Selection of Bibliometric Techniques	Choose appropriate bibliometric techniques based on research objectives (co-citation analysis, keyword co-occurrence analysis, bibliographic coupling).	VOSviewer, CiteSpace	Identification of suitable analysis techniques.
Data Analysis	Conduct the analysis using chosen techniques.	R, Python, VOSviewer, CiteSpace	Insights and patterns in the literature.
Visualization	Visualize the results to aid interpretation and presentation.	VOSviewer, CiteSpace, Bibliometrix	Graphs, maps, and other visual representations of data.
Interpretation and Reporting	Interpret the results and prepare a report detailing the findings and their implications.	MS Word, LaTeX	A comprehensive report with insights and recommendations.

2.2 Visualization

VOSviewer is a bibliometric analysis tool used to create and visualize bibliometric networks. It supports Web of Science, Scopus, Dimensions, and PubMed data. Unlike other tools, VOSviewer integrates clustering methods for analyzing co-citation and co-occurrence networks and a text-mining function for mapping key noun phrases. Its main strength lies in visualization. Key analyses include citation analysis, which identifies influential authors, institutions, and nations, co-authorship analysis, which maps collaboration patterns, and keyword co-occurrence analysis, which reveals dominant research themes and emerging trends. These features make VOSviewer a valuable tool for exploring research landscapes, including blockchain studies (Heriyanti et al., 2022;Ahn et al., 2024).

2.3 Bibliometric Data Collection and Processing

In this study, a comprehensive bibliometric analysis was conducted to explore the integration of BCT within the biotechnology sector.

2.3.1 Bibliometric Data Collection and Processing of the Genetics Field

I will start with the genetics field and explain this process's details. To ensure a robust and reliable dataset, the following methodology was employed:

- **Search Strategy**

I retrieved bibliographic data from Scopus, one of the most reputable and extensive databases of peer-reviewed literature. Scopus was chosen due to its advanced search capabilities and compatibility with bibliometric tools like VOSviewer and Bibliometrix.

The keyword combinations are going to make or break the quality and relevance of the results. For the search query, we have two terms to use, either “OR” or “AND”. These are Boolean operators, and they determine (Zhang & Eichmann-Kalwara, 2019).

- “OR” is used for a wider search net, it’s a way to expand the search, it’s used for synonyms, related terms, or variations. It's great for catching everything relevant across different phrasings.
- “AND” is used for narrower, more targeted search, it combines two or more ideas in the same article

A carefully designed search query was formulated using keywords such as in the years between 2020 and 2025, we also chose to include only peer-reviewed articles and reviews, which carry the most scholarly weight. They're typically the most cited, high-quality, and consistent sources. Including only these reduces noise from non-scholarly materials like conference abstracts, editorials, letters, etc.

Otherwise, include only articles and reviews in our research because it's the best for trend analysis, citation analysis, co-authorship, co-citation, and keyword mapping. Also, the results were filtered by English to avoid translation inconsistencies or misinterpretations, and it keeps the data clean.

The search queries applied for the genetics sector:

- “blockchain”AND “genetic” : 216 results.
- “blockchain” AND “genetic” AND “biotechnology”: 1 article.
- “blockchain” AND “genetic” AND “supply chain”: 20 results.

This helped capture a wide range of publications related to blockchain applications in genetics, biotechnology and supply chain. Filters were applied to limit results to journal articles and reviews only in english language from 2020 to 2025, ensuring both relevance and recency.

- **Screening and Filtering**

After exporting the results in an Excel format and merging the two files, duplicates were removed to reduce bias. I also excluded irrelevant documents that only mention blockchain in passing or in unrelated contexts outside genetics. The final dataset was curated to include only high-quality, thematically relevant records, resulting in an Excel file with 216 articles, as summarized in Figure 11. The chart uses a PRISMA-like format with four stages: Identification, Screening, Eligibility, and Inclusion.

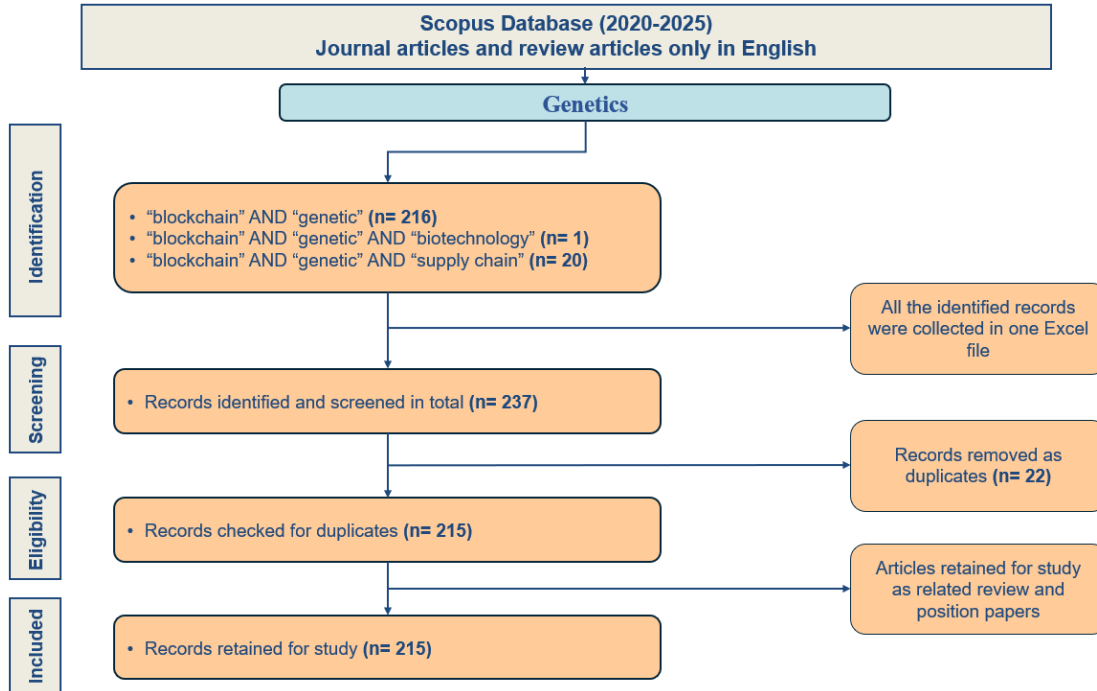


Figure 11: Flow diagram for data collection and refinement for bibliometric analysis of blockchain applications in genetic engineering (2020–2025).

- **Data Cleaning and Standardization**

Synonyms and variants were unified ("blockchain technology" → "blockchain"). Keywords were standardized to align terminology ("internet of things" → "iot").

- **Analysis and Visualization**

Using tools like **VOSviewer**, I performed Co-occurrence analysis of keywords to identify thematic clusters. It reveals how frequently certain terms appear together in the literature.

2.3.2 Bibliometric Data Collection and Processing of Environmental Biotechnology and Bioenergy

For the bibliometric data collection and processing of environmental biotechnology and bioenergy, we focused on how blockchain intersects with environmental biotechnology and bioenergy. During the identification phase, particular keyword combinations were searched for as shows Figure 12, yielding 5,442 entries in total 4,926 unique journal articles and article reviews remained and were included in the study. These articles were deemed relevant as they consisted of review and position papers. The process emphasizes a rigorous and methodical approach to filtering the

most pertinent literature in English related to blockchain applications in environmental and bioenergy contexts.

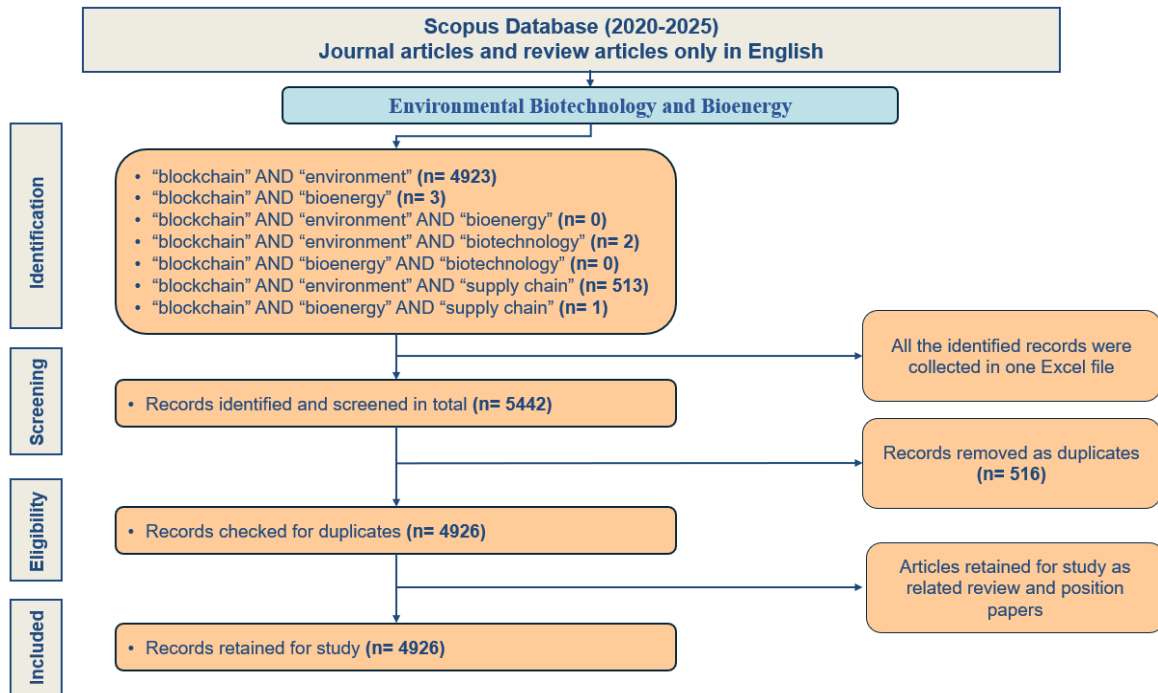


Figure 12: Flow diagram for data collection and refinement for bibliometric analysis of blockchain applications in environmental biotechnology and bioenergy (2020–2025).

2.3.3 Bibliometric Data Collection and Processing of Medical Biotechnology

The flowchart (Figure 13) illustrates the methodological steps followed in conducting a bibliometric analysis on blockchain applications in medical biotechnology from 2020 to 2025, including only journal articles and article reviews only in English language. The process began with a comprehensive literature search in the Scopus database using three keyword combinations: ("blockchain" AND "medical"), ("blockchain" AND "medical" AND "biotechnology"), and ("blockchain" AND "medical" AND "supply chain"). This initial query yielded 2,393 records. After removing 172 duplicate entries, 2221 unique documents remained. The final dataset of articles serves as the foundation for bibliometric analysis, enabling the exploration of research trends, authorship networks, and thematic development in the intersection of BCT and medical biotechnological innovations.

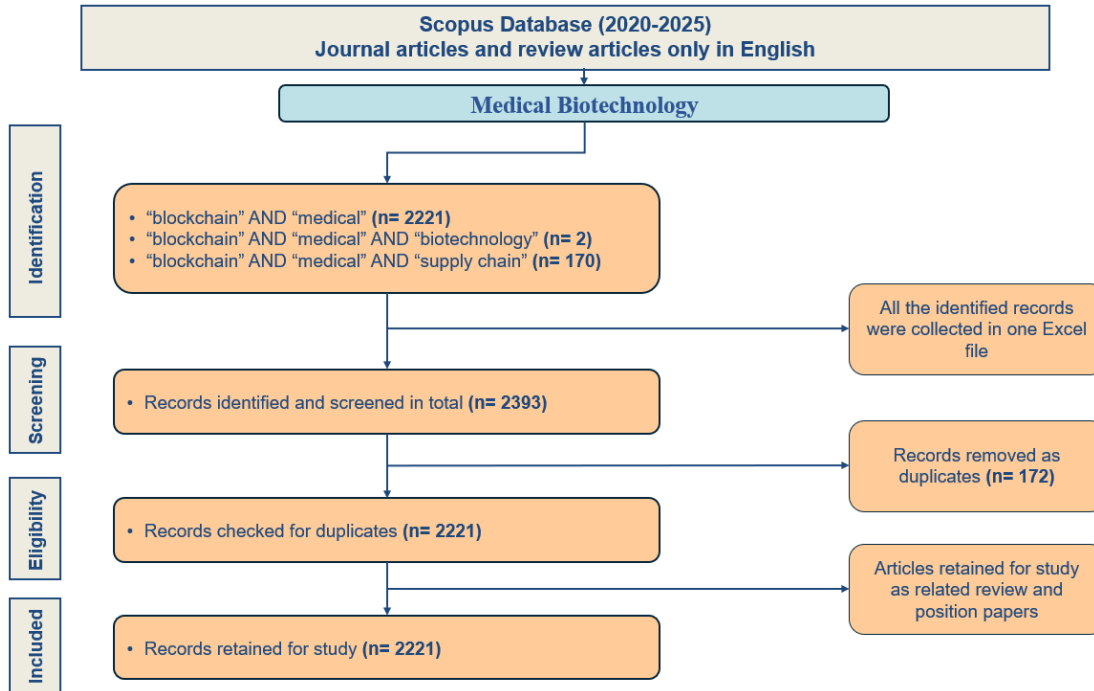


Figure 13: Flow diagram for data collection and refinement for bibliometric analysis of blockchain applications in medical biotechnology (2020–2025).

2.3.4 Bibliometric Data Collection and Processing of Marine Biotechnology

The analytical procedures used to do a bibliometric analysis on blockchain applications in marine biotechnology from 2020 to 2025, incorporating only journal papers and article reviews in the English language, are depicted in the flowchart (Figure 14). Using three keyword combinations: ("blockchain" AND "marine"), ("blockchain" AND "marine" AND "biotechnology"), and ("blockchain" AND "marine" AND "supply chain"). This first search produced 52 records. 43 distinct documents were left after nine duplicate entries were eliminated. In order to explore research patterns, authorship networks, and topic development at the interactions of BCT and marine biotechnology breakthroughs, bibliometric analysis is conducted using the final dataset of publications.

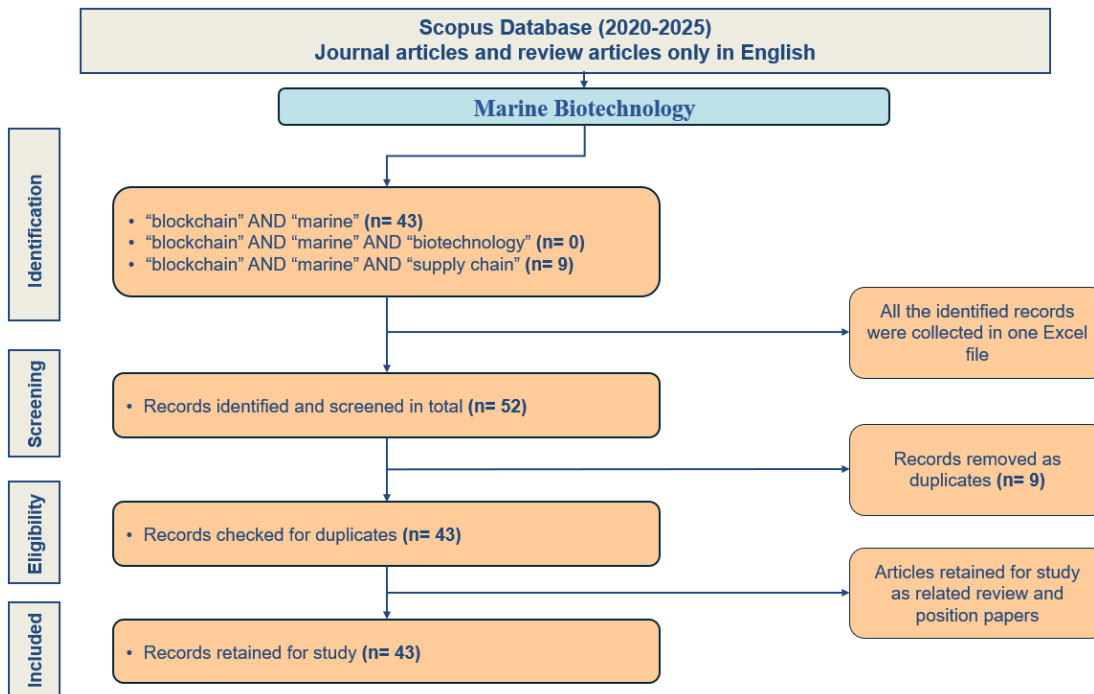


Figure 14: Flow diagram for data collection and refinement for bibliometric analysis of blockchain applications in marine biotechnology (2020–2025).

2.3.5 Bibliometric Data Collection and Processing of Cosmetic and Pharmaceutical Biotechnology

Figure 15 is a flow diagram illustrating the screening and selection process for a bibliometric study using the Scopus database (2020–2025) focused on the role of blockchain in cosmetic and pharmaceutical biotechnology. I conducted a keyword-based search for journal and review articles in English, identifying a total of 403 records using various combinations of terms like “blockchain,” “cosmetic,” “pharmaceutical,” “biotechnology,” and “supply chain.” After compiling all results in an Excel file, 153 duplicate records were removed, resulting in 250 unique articles. These articles were deemed eligible and retained for the study as they were related review and position papers.

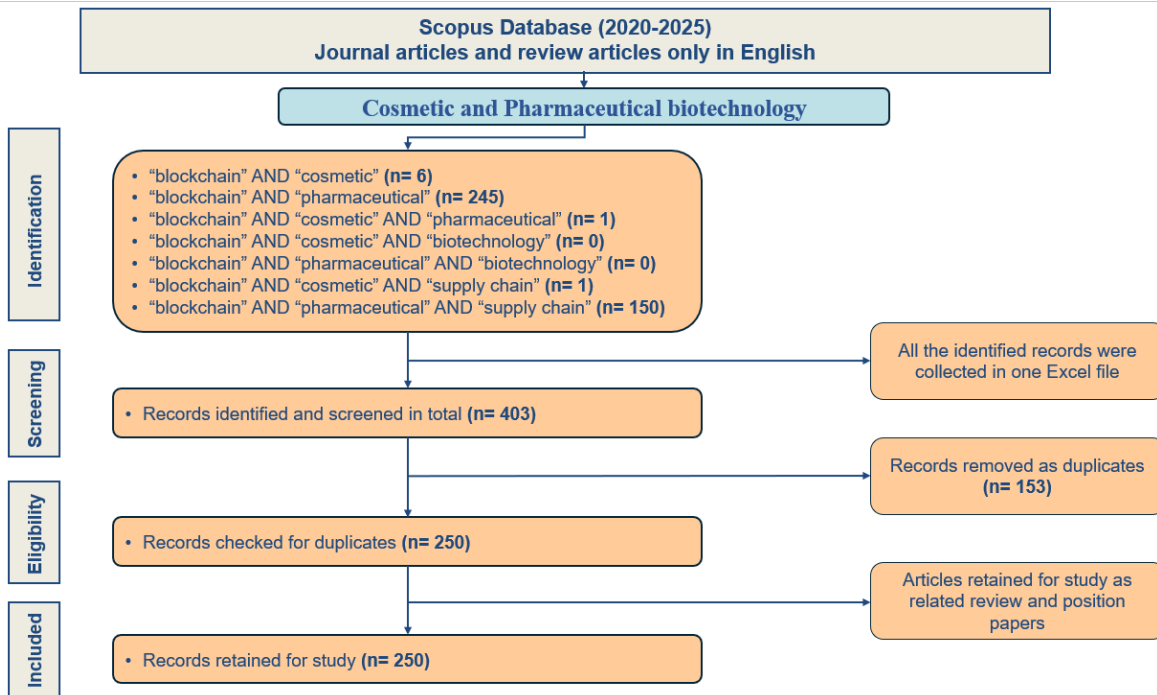


Figure 15: Flow diagram for data collection and refinement for bibliometric analysis of blockchain applications in cosmetic and pharmaceutical biotechnology (2020–2025).

2.3.6 Bibliometric Data Collection and Processing of Agriculture and Food Biotechnology

This diagram (Figure 16) outlines the systematic retrieval and filtering process for a bibliometric analysis on the integration of BCT in agriculture and food biotechnology, based on English journal and review articles indexed in Scopus from 2020 to 2025. Using targeted keyword combinations such as “blockchain,” “agriculture,” “food,” and “supply chain”. The initial search produced 2,908 articles. These records were first consolidated into a single Excel file, then rigorously screened to eliminate 1,531 duplicates. The remaining 1,377 articles were selected for their relevance, specifically those classified as review or position papers, ensuring a transparent and reproducible approach to study selection.

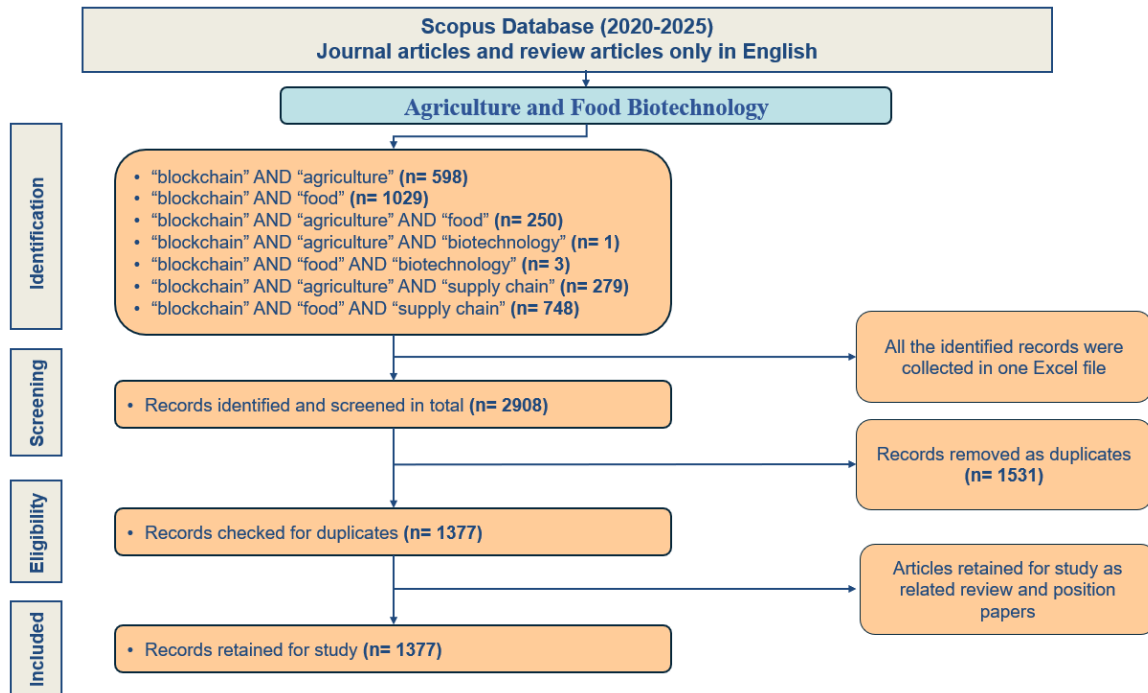


Figure 16: Flow diagram for data collection and refinement for bibliometric analysis of blockchain applications in agriculture and food biotechnology (2020–2025).

After collecting the data for all topics, the next step is data cleaning and standardization to ensure consistency and accuracy. This involves correcting variations in author names (“J. Smith” vs. “John Smith”), unifying keywords (“blockchain” and “block chain”, “Internet of Things” and “IoT”). Once the data is clean, we’ll proceed with the visualization using VOSviewer. This tool will help us create maps showing keyword co-occurrence (common themes like “blockchain,” “supply chain,” “traceability” and “IoT”). This will help us explore co-authorship networks, keyword trends, citation patterns, and the evolution of research themes in the field of blockchain applications in biotechnology.

2.3.7 Data Collection of the Combined Sectors of Biotechnology

The diagram below (Figure 17) shows the data collected from all the files created for each of the six sectors of biotechnology that we chose to work with, it outlines the integration of BCT in biotechnology sectors. The initial data collection produced 9,032 articles. These records were first consolidated into a single Excel file, then rigorously screened to eliminate 730 duplicates. The remaining 8,302 articles were selected for their relevance, specifically those classified as review or position papers. ensuring a transparent and reproducible approach to study selection.

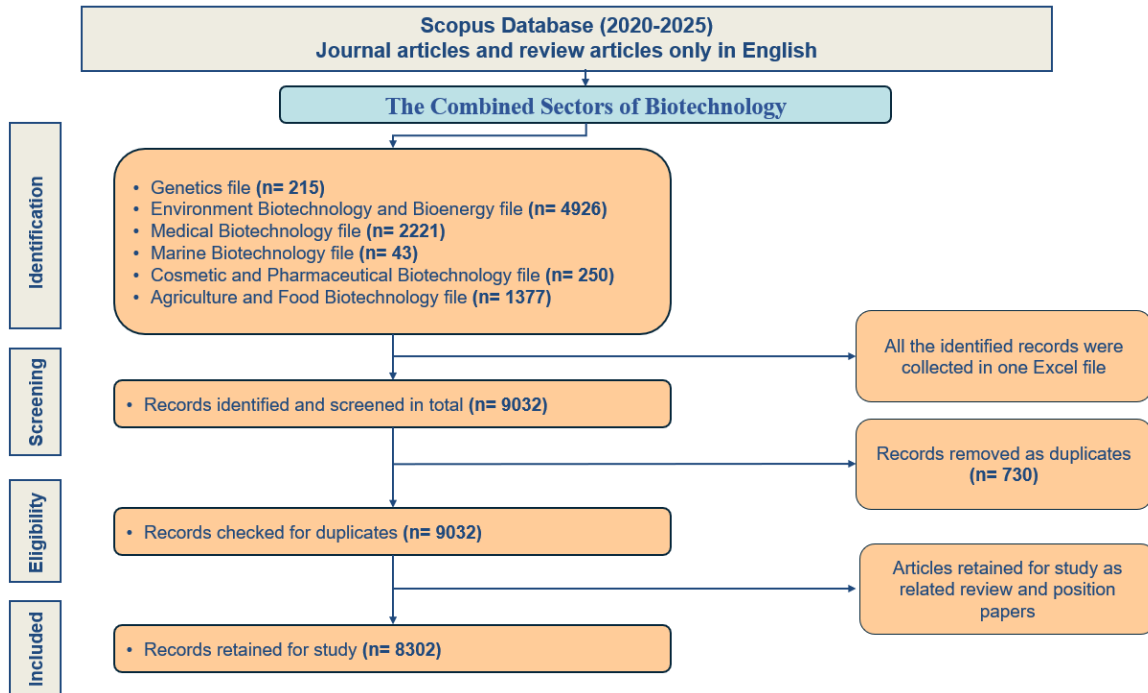


Figure 17: Flow diagram for data collection and refinement of blockchain applications in the combined sectors of biotechnology (2020–2025).

We have created this data file to Highlight influential countries leading research in the integration of the combined sectors of biotechnology.

2.4. Strategic Assessment of Blockchain Integration in Biotechnology: A SWOT Analysis

SWOT analysis stands for: **S**trengths, **W**eaknesses, **O**pportunities, **T**hreats. It’s a strategic planning tool used for identifying and evaluating internal and external aspects that may affect the success of a project, business, research activity, or even one’s own professional development.

According to Gurel & Tat (2017), SWOT analysis is “a strategic planning technique that provides the framework for identifying and analyzing the internal and external environment of an organization or decision context.”. By providing decision-makers with a comprehensive awareness of their internal and external environments, SWOT analysis is a useful tool that facilitates strategic clarity and allows them to make better decisions. By recognizing strengths and weaknesses, it facilitates resource alignment and enables teams to more efficiently distribute resources and efforts. By identifying possible hazards and assisting in their anticipation and mitigation, it also improves risk management. It promotes innovative thinking and proactive planning by spotting outside chances. In the biotechnology industry, this method is very helpful since it may direct

decisions on product development, R&D tactics, regulatory planning, and market entry (GÜREL & TAT, 2017).

Integrating BCT into biotechnology represents a transformative frontier with significant implications for data security, supply chain management, and research collaboration.

To conduct a strategic SWOT analysis of blockchain integration in biotechnology, we began by clearly defining our objective, such as improving data integrity, enhancing supply chain traceability, or securing intellectual property, so the analysis remains focused, targeted and beneficial. Next, evaluate internal factors by identifying strengths like enhanced traceability and transparency, data security and integrity, smart contract automation also its decentralization, as well as weaknesses such as scalability limitations, energy consumption and lack of industry-wide standards. Then, assess external factors by exploring opportunities, including convergence with AI, IoT and big data analytics, and the automation of regulatory compliance processes, while also identifying threats such as regulatory uncertainty, high implementation costs, and the resistance to change from established stakeholders. This data will be entered into a SWOT matrix (Nwagwu Bachelor, 2020).

3. RESULTS AND DISCUSSION

In this section, the results from the different phases of this bibliometric analysis, including visualizations of the collected data and their interpretations, are presented and discussed.

3.1 Keyword Co-occurrence Results

Keyword co-occurrence is a bibliometric analysis method that examines how frequently pairs of keywords appear together within a set of documents, providing information on the connections between study topics and the organization of a scientific field. Finding core themes, new trends, and the connections between ideas within a given field are all made possible by this method. Through a multi-step process, VOSviewer makes this analysis easier. First, it uses co-occurrence data to generate a similarity matrix. Next, it uses a mapping technique to place keywords in a low-dimensional space where the distance between any two keywords indicates how related they are. The resulting visualizations display keywords as nodes, with their size representing frequency and proximity indicating the strength of their association.

This approach has been used to reveal the development of study areas in various fields. Researchers can obtain a thorough grasp of the conceptual terrain of a field of study by examining keyword co-occurrence, which enables more thoughtful and methodical examination of scientific literature (van Eck & Waltman, 2010).

We present the resulting bibliometric maps that focus on exploring the impact of BCT within the biotechnology field, we will start with:

- **Environmental Biotechnology and Bioenergy**

This co-occurrence map created in VOSviewer (Figure 18) visualizes keyword relationships of the impact of BCT within the environmental biotechnology and bioenergy field. The keyword “blockchain” emerges as the most central and frequently co-occurring term, underscoring its foundational role across diverse domains. Its central position reflects blockchain’s potential as a convergence technology, enabling secure, transparent, and decentralized processes across environmental and biotechnological applications.

➤ **Green Cluster: BCT Foundations**

This cluster captures the technical and structural core of blockchain include Keywords as: Smart contract, Ethereum, Bitcoin, Consensus, Hyperledger fabric, peer-to-peer computing, and distributed systems. This backbone cluster illustrates the technology foundations that support blockchain applications (W. Wang et al., 2024).

➤ **Blue Cluster: Data & Cloud Infrastructure**

This one represents themes of data governance, particularly relevant in biotechnology and environmental systems (data sharing, data storage, cloud computing, access control, privacy protection, authorization and information management).

This indicates that blockchain is being explored as a tool for secure data sharing and cloud-based architecture (W. Wang et al., 2024).

➤ **Purple Cluster: Security & Cryptography**

Here the focus is on cybersecurity aspects: IoT, security, digital storage and privacy preserving. This supports blockchain's role in secure data environments which are crucial in environmental biotechnology, where privacy and integrity of data are key (W. Wang et al., 2024).

➤ **Yellow Cluster: Network, and Authentication**

This cluster focuses on the integration of blockchain with IoT and communication systems: IoT, network security, security, network architecture, authentication, fog computing, Internet of vehicles, vehicular networks.

It highlights the potential of blockchain in smart device ecosystems, which may have anything to do with biosensors or biotechnological environmental monitoring tools.

The bibliometric analysis reveals a rapidly evolving convergence between BCT and environmental biotechnology, marked by strong interdisciplinary intersections and forward-looking trends. Blockchain is increasingly combined with technologies like AI, IoT, cryptography, and cloud computing to create intelligent, transparent ecosystems that can handle challenging environmental issues. Significant developments such as decentralized bioinformatics platforms and sustainable supply chains highlight a paradigm change in which blockchain moves from a supporting function to a fundamental infrastructure in the environment sector.

- **Genetics**

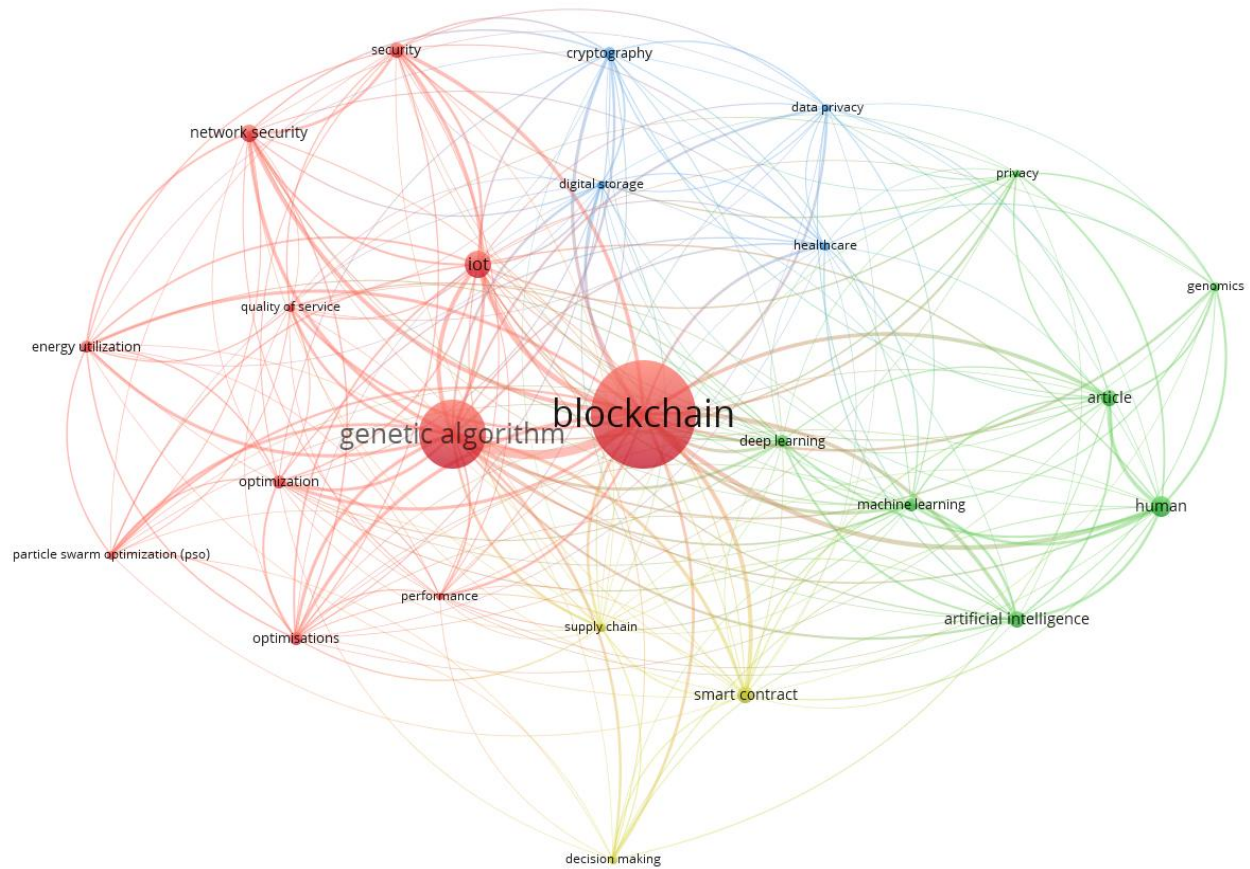


Figure 19: Keyword Co-occurrence Network of Blockchain Applications in Genetics (2020–2025): A Bibliometric Analysis.

Figure 19 is a co-occurrence map created in VOSviewer, visualizes keyword relationships of the impact of BCT within the genetics field. Once more, "blockchain" is central, serving as a link between the fields of genetics, optimization algorithms, and security. Its centrality suggests that it is being effectively incorporated into various biotechnology application cases rather than merely being included as a trendy term. We will summarize the other clusters in Table 4.

Table 4. Identified research clusters from Co-occurrence mapping of genetics (Paramesha et al., 2024).

Cluster Color	Theme	Core Keywords	Biotechnology Implications
Red	Optimization & IoT Systems	Blockchain, genetic algorithm, IoT, optimization, energy utilization, etc.	Blockchain could be used to secure and optimize genomic data pipelines and real-time health monitoring systems, ensuring both performance and privacy.

Green	AI-Driven Genomics & Privacy	genomics, AI, human, & privacy, ML.	BCT is essential for protecting sensitive genomic data in precision diagnostics and personalized medicine, particularly since AI models require a lot of human data.
Blue	Data Security & Cryptography	cryptography, healthcare, digital storage, data privacy	Blockchain cryptographic systems offer decentralized, tamper-proof storage for health records, genetic test results, and research data.
Yellow	Governance & Automation	smart contract, decision making and supply chain	permits reliable cooperation across various parties when genetic data is exchanged or licensed, including labs, research institutes, and hospitals.

According to the map, BCT and genetics increasingly work together to create secure, effective, and customized biotech solutions. The optimization of bioinformatics systems, automation via smart contracts, and data privacy in genomics are essential topics. Despite the encouraging trends, there are still issues with ethical frameworks and practical application. More interdisciplinary research and cooperation are needed to fully realize blockchain's potential in genetic science and customized medicine.

- **Medical Biotechnology**

Figure 20 is a co-occurrence map created in VOSviewer, visualizes keyword relationships of the impact of BCT within medical biotechnology. Otherwise, Table 5 describes and interprets the core clusters of the map.

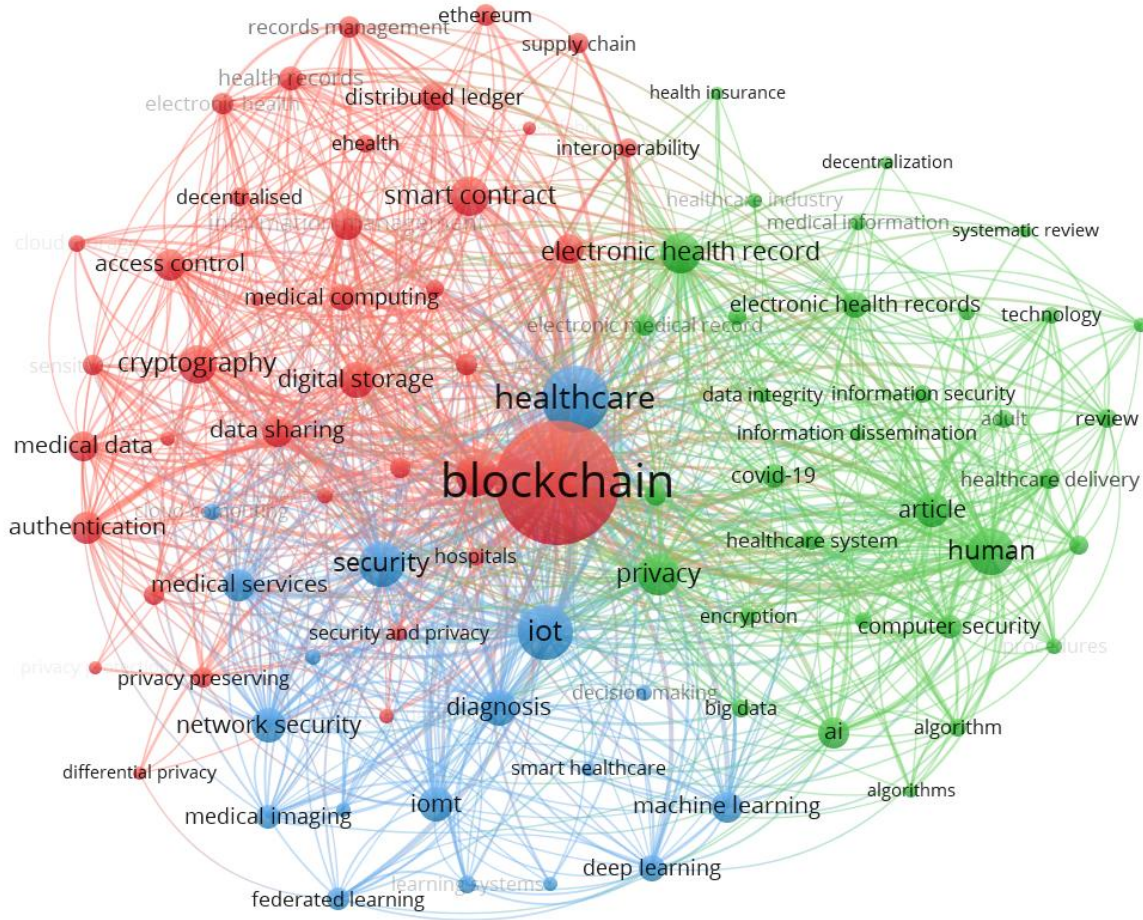


Figure 20: Keyword Co-occurrence Network of Blockchain Applications in Medical Biotechnology (2020–2025): A Bibliometric Analysis.

Table 5. Identified research clusters from Co-occurrence mapping of medical biotechnology (Rejeb et al., 2021).

Cluster Color	Theme	Core Keywords	Biotechnology Implications
Red	Data Security, Cryptography, and System Architecture	Blockchain, cryptography, authentication, access control, data privacy, sensitive data, medical data, distributed ledger, information management, smart contract	This cluster highlights how distributed ledger technology (DLT) and cryptographic techniques can be used to secure hospital data and medical records. It reflects the need for secure, impenetrable mechanisms for accessing and storing medical data.
Blue	IoT and AI-Powered Diagnosis in Healthcare	IoT, IoMT, medical imaging, diagnosis, DL, federated learning, edge computing,	This cluster emphasizes how blockchain, AI, and IoT may be combined to improve data processing, wearable technology, and diagnostic accuracy in healthcare monitoring.

		security, ML, cyber security, smart healthcare	It displays cutting-edge technologies that aid in clinical decision-making.
Green	Health Records, Telemedicine, and Patient-Centric Care	Healthcare, electronic health records (EHR), health data, telemedicine, human, delivery of healthcare, review, article, health insurance, interoperability, information systems.	This cluster focuses on blockchain's impact on patient data management and telemedicine. It demonstrates how blockchain enhances safe data interchange, interoperability, and effective healthcare delivery, particularly via decentralized digital platforms and EHR systems (Medicalchain) (Zhou et al., 2024).

This analysis highlights blockchain's central role in advancing healthcare biotechnology by enhancing data security, interoperability, and smart healthcare delivery. Its integration with AI, Internet of Medical Things (IoMT), and EHR systems support secure diagnostics, privacy protection, and efficient patient care. The findings emphasize blockchain's growing impact as a key enabler of trust, transparency, and innovation in digital medical ecosystems.

- **Marine Biotechnology**

This VOSviewer map (Figure 21) displays a straightforward yet informative keyword co-occurrence network that connects the marine environment, blockchain and the IoT. There is growing interdisciplinary interest in using blockchain for environmental monitoring, as seen by the central node blockchain's connections to the marine industry and the Internet of Things. While the relationship to IoT emphasizes the combination of smart sensors and blockchain for real-time secure data collecting, the connection to "marine environment" suggests possible applications like tracking marine pollution or sustainable fisheries. This map, despite its sparsity, indicates a developing study area at the intersection of maritime sustainability and digital innovation.

The reason our VOSviewer map shows only a few keywords and clusters is because the topic is still very new and not widely researched. We found only 43 articles, less standardized terminology, and lower keyword repetition, which results in a simpler map.

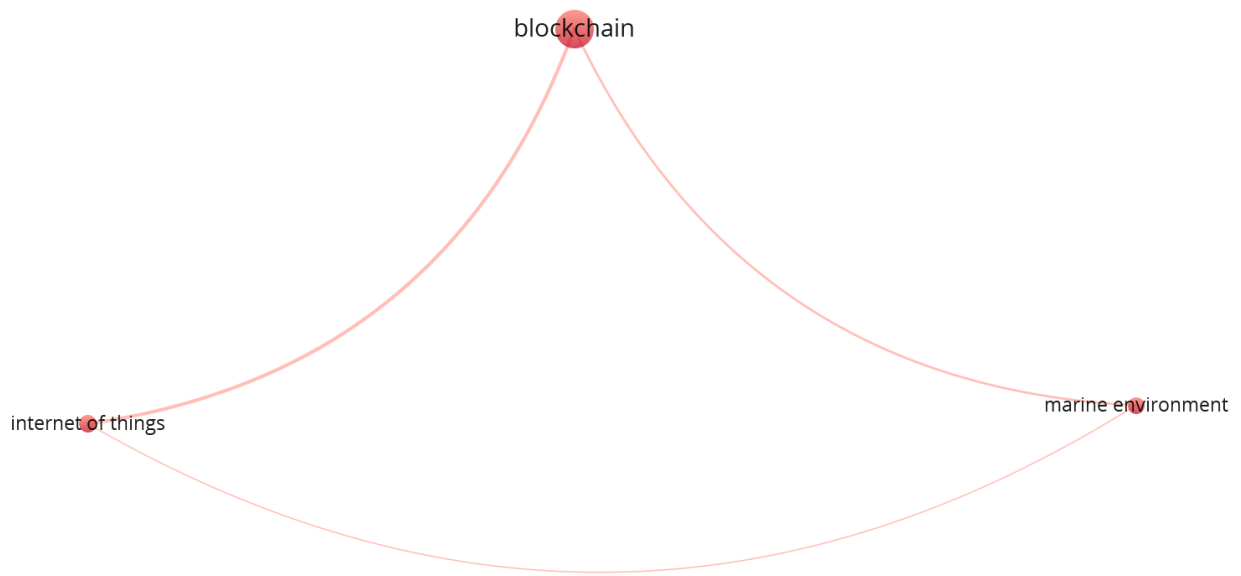


Figure 21: Keyword Co-occurrence Network of Blockchain Applications in Marine Biotechnology (2020–2025): A Bibliometric Analysis.

- **Agriculture and Food Biotechnology**

The keyword co-occurrence map (Figure 22) reveals a diverse and interlinked research ecosystem surrounding blockchain in agriculture, biotechnology, and sustainability. Notably, the research landscape is changing to encompass important societal issues like sustainability, food security, and consumer trust in addition to technological advancements like AI, smart contracts, and IoT. The combination of supply chain openness, smart agriculture, and data privacy points to a move toward an all-encompassing digital transformation of agri-food systems.

Also, in Table 6 we explained the identified research clusters from our generated co-occurrence mapping of agriculture and food biotechnology.

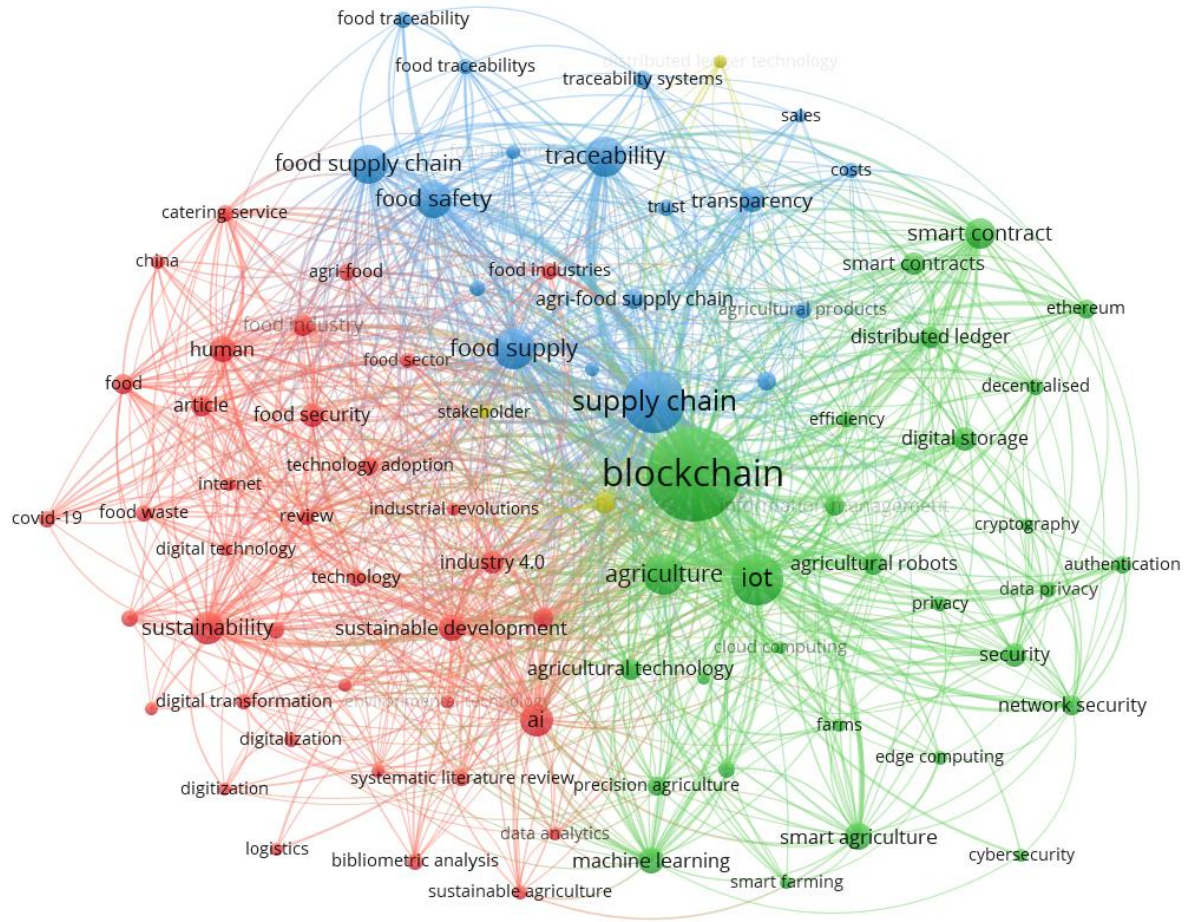


Figure 22: Keyword Co-occurrence Network of Blockchain Applications in Agriculture and Food Biotechnology (2020–2025): A Bibliometric Analysis.

Table 6. Identified research clusters from Co-occurrence mapping of agriculture and food biotechnology (Niknejad et al., 2021).

Cluster Color	Theme	Core Keywords	Biotechnology Implications
Green	Tech-Driven Smart Agriculture	blockchain, IoT, agriculture, agricultural robots, distributed ledger, smart contracts, smart farming etc.	This cluster focuses on how blockchain and IoT are transforming agriculture digitally. With the aid of AI, smart contracts, and precision agriculture technologies, it aims to increase farming's automation, efficiency, and transparency. The three main issues are data management, decentralization, and security.
Blue	Supply Chain & Traceability Systems	traceability, Food supply chain, food traceability, food safety, agri-food supply chain etc.	This cluster emphasizes food supply chain safety and traceability. Here, research focuses on using blockchain technology to guarantee transparent,

			reliable, and effective food safety and quality monitoring from production to consumption.
Red	Sustainability & Food Security	sustainability, food waste, AI, food security, technology adoption, industry 4.0, food industry, human, etc.	Food security and sustainable food systems are the main topics of this cluster. It looks at how blockchain and digital technology may help with global issues including pandemics (like COVID-19), food waste, and climate change while promoting sustainable farming methods and fair access to food.

- **Cosmetic and Pharmaceutical Biotechnology**

BCT is revolutionizing pharmaceutical and cosmetic biotechnology, according to the bibliometric analysis. Three primary themes are centered on research trends: enhancing supply chain transparency, protecting healthcare data, and using BCT with AI for innovation and diagnostics as shows in Figure 23 and Table 7. This demonstrates the increasing importance of blockchain as a multipurpose instrument that improves efficiency, security, and trust throughout the industry (Singh et al., 2023).

pharmaceutical industry,
authentication.

3.1.1 Interpretive Summary

The generated keyword co-occurrence maps reveal how BCT is being incorporated into contemporary biotech innovation in a clear and expanding way. Across fields from environmental biotechnology and genetics to agriculture, medicine and pharmaceutical, blockchain consistently emerges as a central node, reflecting its role in enabling secure, decentralized, and transparent systems. Although blockchain is used differently in each domain, for example, to protect genomic data, improve supply chain traceability, or facilitate intelligent healthcare delivery, common themes include the convergence of advanced data governance structures, AI and IoT. These technologies are collectively shaping intelligent ecosystems capable of addressing complex challenges such as data privacy, sustainability, and efficiency. Although research maturity varies, with marine biotechnology being at an earlier stage than the more advanced medical or agricultural industries, the general trend indicates that blockchain will move from supporting innovation to being a key driver of it. This change not only emphasizes the multidisciplinary character of contemporary biotech research, but it also shows how BCT could revolutionize data-centric, ethically grounded, and technologically integrated biotechnological systems.

3.2 Country Co-Citation Analysis Results

The main purpose of creating this density map (Figure 24) is to visualize the intellectual structure and collaboration patterns of countries contributing to the intersection of BCT and biotechnology.

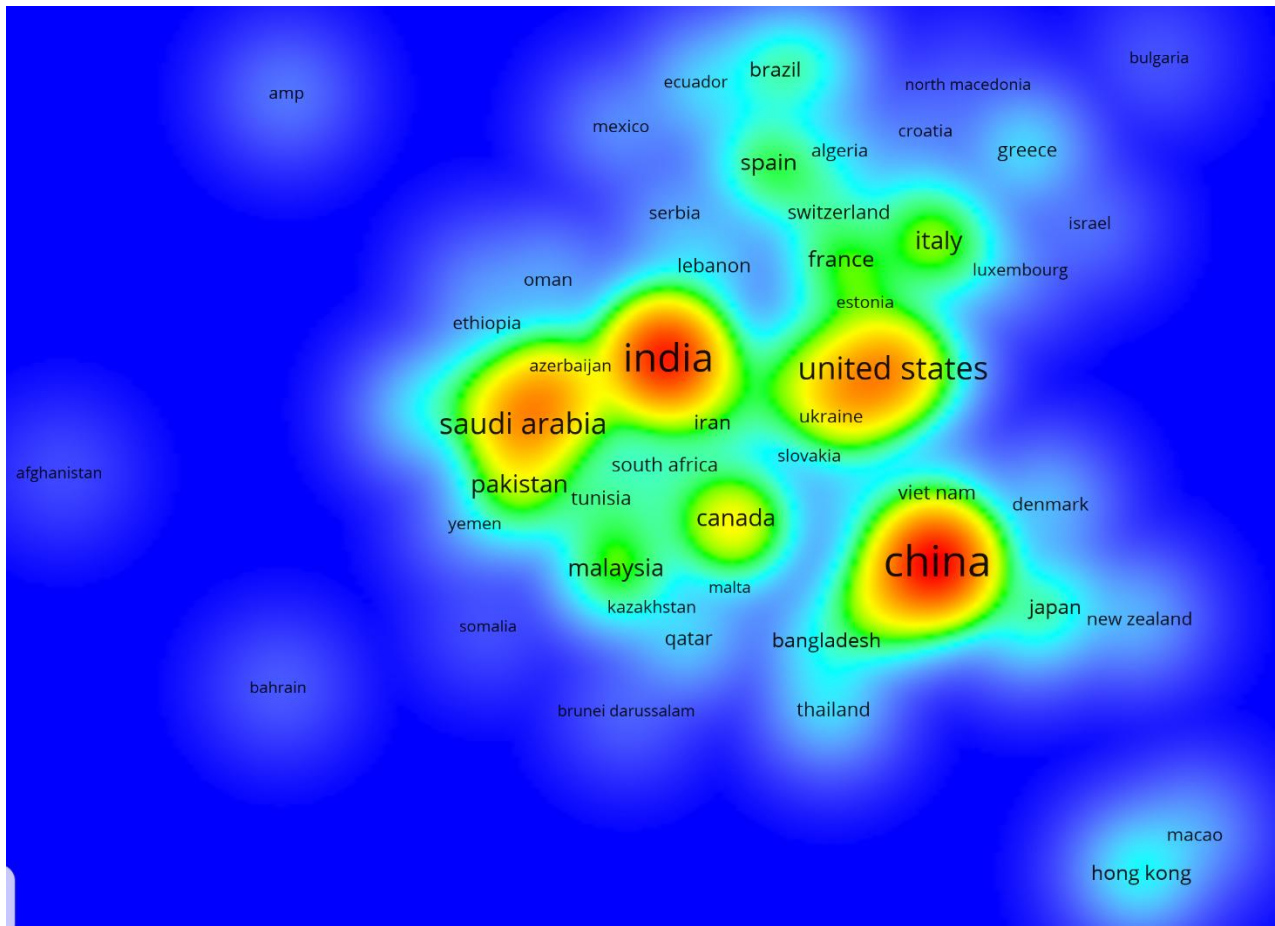


Figure 24: Mapping the intellectual landscape of Blockchain-Biotechnology research: A Country Co-Citation Analysis.

This visualization represents a country co-citation density map generated by VOSviewer using the data collected of the combined sectors of biotechnology, focusing on the intersection of BCT and biotechnological research. Each country's name is sized according to its frequency of co-citation in the heatmap-style map, larger names denote nations frequently referenced with others in related research articles. The color gradient, which goes from blue to red, signifies density, low co-citation is represented by blue zones, medium activity by yellow and green zones, and high co-citation activity by red zones. Co-citation relationships are also reflected in the spatial arrangement: whereas faraway nations have fewer co-citation ties, closely spaced countries are frequently co-cited in the same research papers or have common study themes.

Analyzing the map reveals several compelling patterns. In the literature on blockchain and biotechnology, Saudi Arabia, China, India, and the United States stand out as the main actors. Their prominent locations, sizable labels, and bright red coloring indicate that they are frequently

cited together and probably play a leading role in research output and cooperation. These nations serve as major hubs for the academic community. They are surrounded by groups of nations that seem to represent regional or thematic alliances. Canada, Malaysia, and Pakistan, for instance, constitute a noteworthy cluster, maybe because of common regional research interests, partnerships, or technological applications. Similarly, the transatlantic network formed by France, Italy, Spain, Switzerland, and Ukraine may represent close European cooperation or academic reference. China, Bangladesh, Vietnam, and Japan seem to be closely clustered in the Asia-Pacific area, indicating a thriving East/Southeast Asian research axis (Daim et al., 2020).

Other nations with intermediate degrees of co-citation, such as Brazil, Iran, South Africa, Malaysia, and Tunisia, are in the green and yellow zones. Although they may not yet be leaders in the area, these countries are becoming more involved and may be new contributors or specialized research communities in the integration of BCT and biotechnology. Their existence indicates that the field is becoming more widely dispersed. Several of countries, including Afghanistan, Bahrain, and Hong Kong, are in blue zones on the map's edges, signifying low levels of co-citation activity. These countries might be underrepresented in cooperative research networks or have little participation in literature. But their existence also points to unrealized possibilities and places where institutional investment or international assistance might encourage more participation (C. Liu et al., 2024).

- **Analytical Reflections**

This co-citation density map offers a rich picture of the global scholarly landscape at the intersection of blockchain and biotechnology. It exposes a research environment that is presently controlled by a small number of superpowers: China, India, Saudi Arabia and the United States. These countries are closely connected to one another by regular co-citation and probably cooperation. Regional clusters also draw attention to the existence of transnational research corridors, including those that connect Europe, East Asia, and South Asia. As new countries enter the research conversation, the area is starting to diversify, as evidenced by the increasing number of moderately participating countries. Crucially, the map also identifies regions that are not as well-integrated into the network, indicating potential avenues for future partnerships and inclusive growth (Biedova & Mahdikhani, 2023). This map also offers guidance for future action. Research networks may become more resilient and creative if cross-regional collaborations are strengthened,

especially those connecting South Asia, East Asia, and the West. Additionally, there is a lot of potential in helping fewer participating nations develop their infrastructure, collaborate with academic institutions, and profit from blockchain-biotech research.

4. BLOCKCHAIN INTEGRATION IN BIOTECHNOLOGY: A CONCEPTUAL FRAMEWORK AND ROADMAP

4.1 A Conceptual Framework for Blockchain Integration in Enzymatic Plastic Recycling: The Case of Carbios

Figure 25 presents a conceptual framework specifically designed to integrate BCT into the enzymatic plastic recycling processes of Carbios, a French biotech company. The framework, which has been modified to meet the unique requirements of a circular bioeconomy, is based on the user-system-information structure seen in health and therapeutic design (HTD) models (Z. Liu et al., 2022). The three integrated layers of the framework are Stakeholders & Operations (Level A), Blockchain-Enhanced Biotech Process (Level B), and Sustainable Data Management & Impact (Level C). In Carbios' enzymatic recycling methodology, each stage focuses on elements that are necessary to achieve complete traceability, automation, and sustainability.

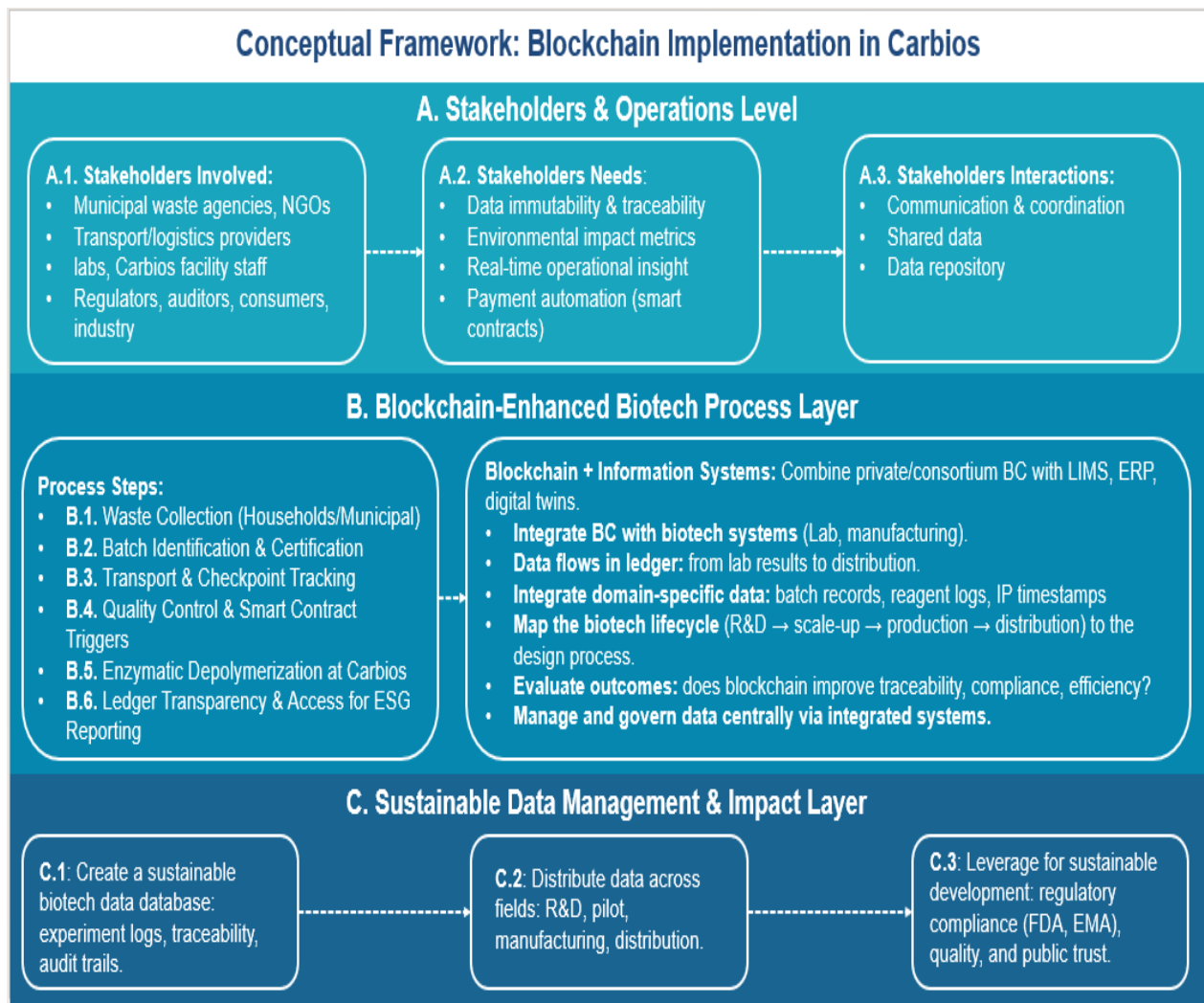


Figure 25: Conceptual Framework for Blockchain Integration in Carbios’ Enzymatic Plastic Recycling Ecosystem.

- **Level A: Stakeholders & Operations Level**

Outlines the organizational and interpersonal environment in which Carbios functions. This comprises end users, NGOs, logistics companies, laboratory and facility employees, auditors, regulators, and municipal trash authorities. These actors need data that is real-time accessible, traceable, and unchangeable. They also gain from automated features like smart contracts, which expedite payments and initiate process reactions. This level highlights the value of cooperation, data exchange, and open communication, all of which can be improved by the safe and decentralized architecture of BCT (Z. Liu et al., 2022).

- **Level B: Blockchain-Enhanced Biotech Process Layer**

Symbolizes the fundamental operational connection between Carbios' enzymatic recycling process and blockchain technology. Waste collection and sorting, batch identification and certification, transport and checkpoint tracking, quality control with smart contract automation, enzymatic depolymerization at the Carbios facility, and ledger transparency for ESG reporting are the six main steps that comprise this layer. Blockchain integration with essential information systems, including digital twins, enterprise resource planning (ERP) platforms, and laboratory information management systems (LIMS), supports these procedures. Complete traceability from R&D to manufacture and distribution is made possible by Carbios's ability to record lab results, reagent records, and processing data in a tamper-proof ledger. Blockchain also aids in determining whether results such as emissions, energy consumption, and product quality are consistent with operational and sustainability objectives (Z. Liu et al., 2022).

- **Level C: Sustainable Data Management & Impact Layer**

Addresses how strong data governance provided by blockchain promotes long-term sustainability. To keep track of experiment logs, audit trails, and traceability records, a specific data repository is established. To provide consistent access to trustworthy information, these datasets are then dispersed throughout organizational functions, including R&D, pilot production, large-scale manufacture, and distribution. Crucially, this layer enables Carbios to adhere to regulatory frameworks like those established by the FDA and EMA as well as worldwide sustainability requirements. Additionally, it makes environmental reporting more transparent, which boosts stakeholder trust and contributes to ESG performance indicators (Z. Liu et al., 2022).

The three levels of this framework show how BCT can be used comprehensively throughout the plastic recycling lifespan of Carbios. Blockchain guarantees traceability, boosts productivity, and facilitates strategic decision-making throughout the whole plastic waste collection process, from enzymatic breakdown to final material recovery. With this approach, Carbios is positioned as a digital leader in sustainable circular economic activities in addition to being a biotechnology innovation (Z. Liu et al., 2022).

4.2 Roadmap for Blockchain Implementation in Biotechnology

The roadmap for blockchain implementation in biotechnology (Figure 26) is organized into five progressive phases, beginning with assessment and strategic planning. Organizations are urged to assess their data systems, team capabilities, regulatory environment, and technology infrastructure

during the first phase, which lasts from 0 to 6 months. A sustainable blockchain strategy is built on a foundation of well-defined objectives, stakeholder identification, and feasibility studies that include evaluations of cost, performance, and risk (Akbar et al., 2022).

In phase two (6–12 months) design and prototyping activities begin, this entails selecting the appropriate blockchain platform (Hyperledger, Ethereum), creating data models, and integrating with pre-existing systems like ERP, LIMS, and Internet of Things devices. A proof of concept is created to replicate particular use cases in a controlled setting after biotechnological processes are converted into smart contract logic. Performance indicators and early feedback aid in design refinement.

The third phase (12–18 months) involves pilot implementation. Dashboards, user interfaces, and blockchain nodes are among the infrastructure that has been deployed. Staff training and success metric tracking are used to support the limited-scale deployment of a particular department or procedure. Performance is continuously tracked, and iterative optimization is used to remove any business or technical bottlenecks.

The fourth phase (18–36 months) is dedicated to expansion and integration. With a focus on ecosystem-wide interoperability and regulatory compliance, the blockchain system is expanded across more departments or partners. Additionally, this phase fosters innovation through the incorporation of AI, ML, and new applications like DeFi-driven biotech finance or NFT-based intellectual property management.

The last stage, which lasts for more than 36 months, symbolizes development and maturity. To measure return on investment (ROI), operational enhancements, and alignment with initial objectives, a thorough impact evaluation is carried out. The organization emphasizes environmental sustainability, formalizes governance systems, and establishes itself as a leader by joining academic and industry consortia. Ongoing research and roadmap improvement foster long-term innovation (Akbar et al., 2022).

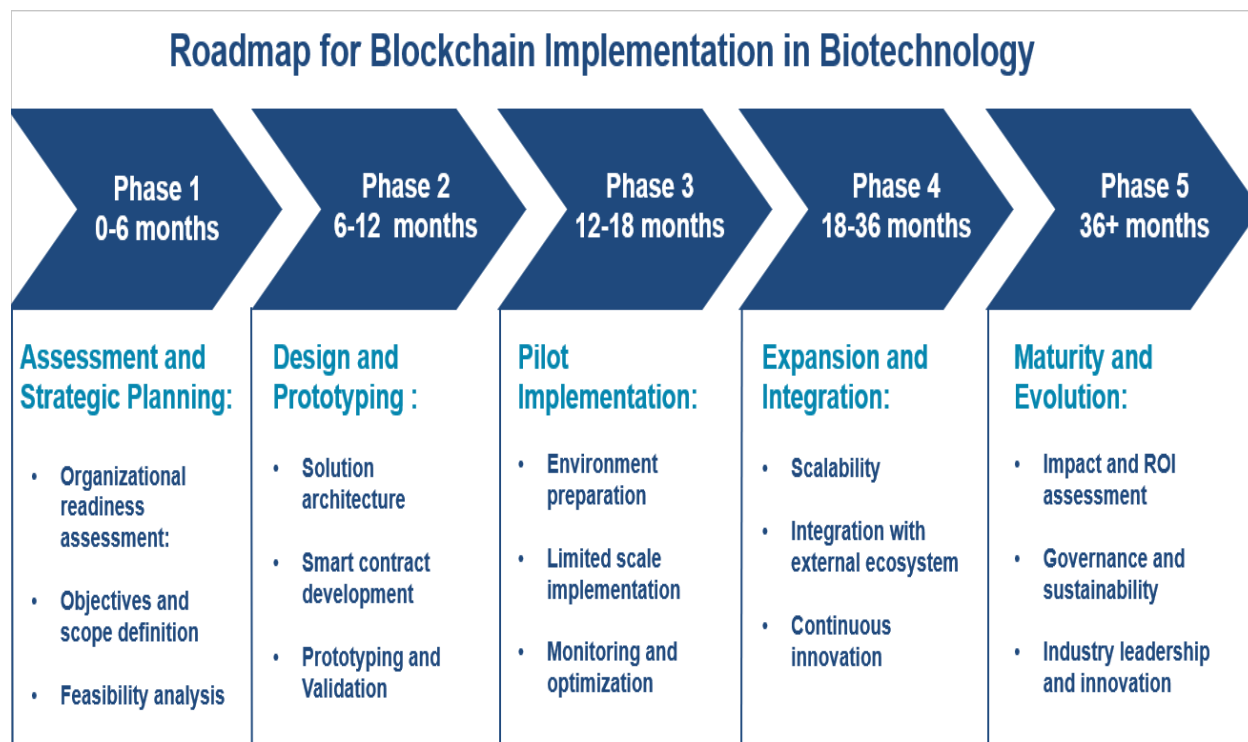


Figure 26: Illustration of a Roadmap for blockchain implementation in biotechnology.

This roadmap can be modified for use in various biotechnology industries. In genomics, for instance, early stages concentrate on consent and privacy, while later stages imagine marketplaces for genomic data. Integrating electronic health records and traceability are key components of medical biotechnology. Blockchain facilitates crop tokenization and farm-to-fork transparency in agriculture. Blockchain facilitates safe data management, enhances compliance, and fosters stakeholder confidence in all industries (Stawicki et al., 2019).

The plan concludes by highlighting important parameters including adoption levels (active users, process coverage), business value (error reduction, regulatory compliance), and technical performance (latency, uptime). Additionally, it tackles issues like regulatory uncertainty, scalability, and resistance to change by providing mitigating techniques like training initiatives, layer 2 solutions, and regulatory engagement. When combined, these components offer a strong, incremental strategy for incorporating BCT into biotechnology in the future (Durá et al., 2023).

5. STRATEGIC ASSESSMENT AND EMERGING TRENDS OF BLOCKCHAIN IN BIOTECHNOLOGY

5.1 Strategic Assessment of Blockchain in Biotechnology: SWOT Analysis Based Insights

This SWOT analysis illustrates Figure 27, derived from our conducted comprehensive bibliometric research, examines the multifaceted landscape of blockchain applications across various biotechnology domains. The present study offers stakeholders a strategic framework for comprehending blockchain's present position and future trajectory in biotechnology by methodically assessing its inherent strengths, enduring shortcomings, upcoming possibilities, and prospective threats. The results show that although blockchain has strong potential to improve data integrity and openness, scalability, technological complexity and legislative ambiguity, need to be resolved to reach its full potential. This evaluation is helpful for researchers, business professionals, and legislators negotiating the intricate relationship between these two groundbreaking technologies as biotechnology develops (Nwagwu Bachelor, 2020).

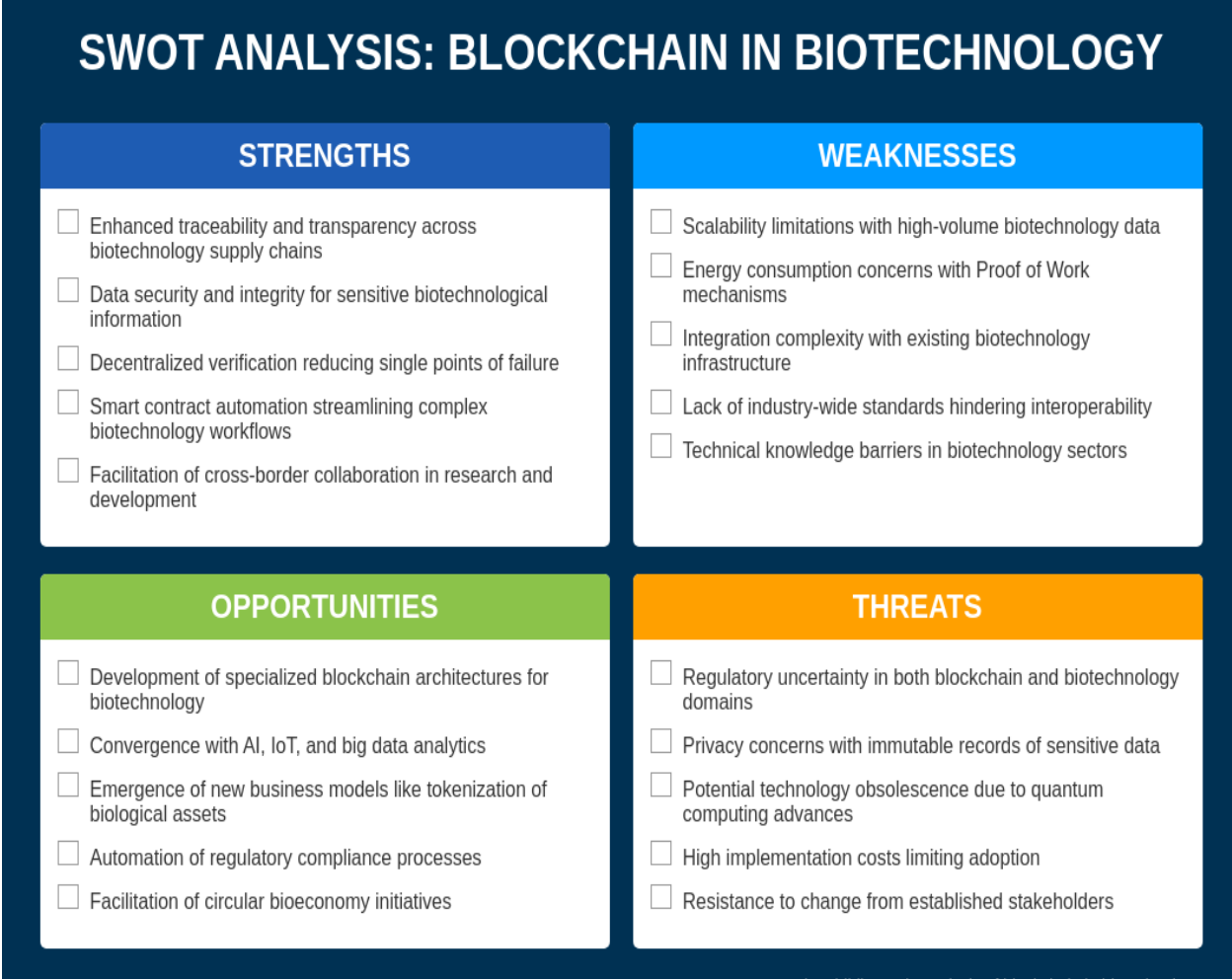


Figure 27: SWOT Analysis: Integration of BCT in Biotechnology.

5.2 Current Insights and Key Future Trends in Blockchain Applications in Healthcare Market (Medical Biotechnology)

The future of BCT in medical biotechnology represents a transformative paradigm shift that extends far beyond simple data management, with market projections confirming this trajectory. The global blockchain market for healthcare was valued at USD 9.56 billion in 2024 and is expected to increase at a compound annual growth rate (CAGR) of 35.08% from 2025 to 2034, reaching approximately USD 193.43 billion (Figure 28).

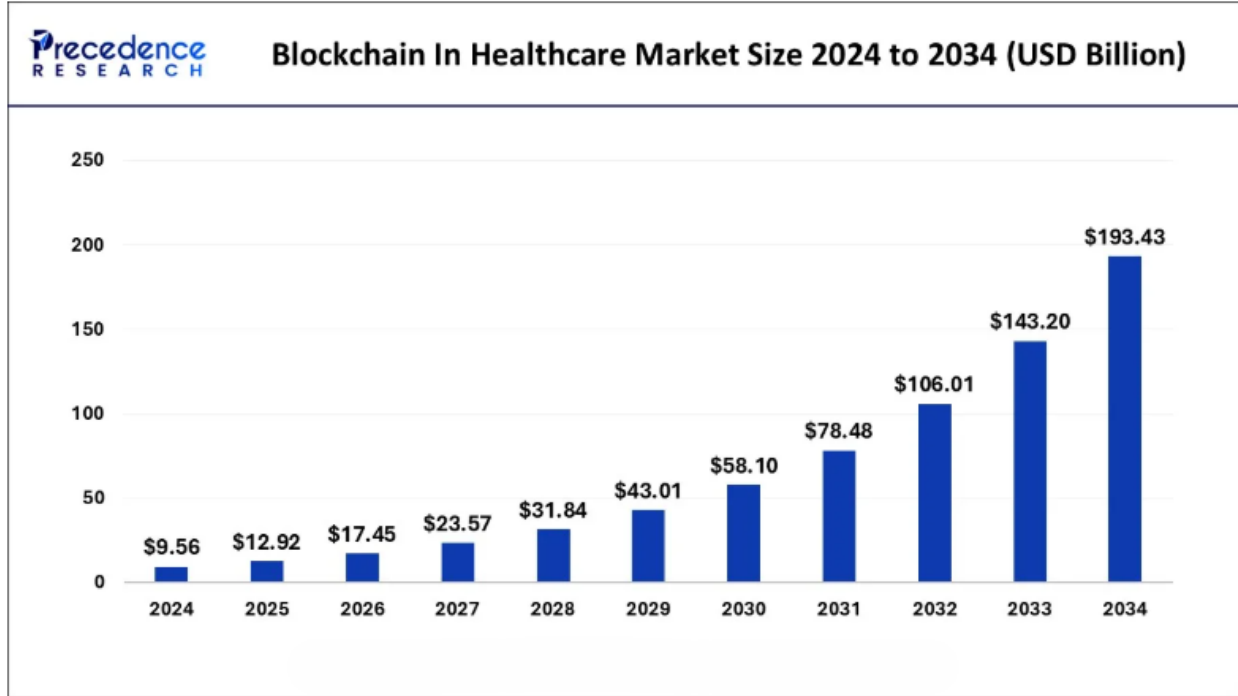


Figure 28: Global Expansion: Blockchain in Healthcare Market Projected to Surge to \$193.43 Billion by 2034 (Blockchain in Healthcare Market Size to Hit USD 193.43 Bn by 2034, 2025), Retrieved June 4, 2025, from <https://www.precedenceresearch.com/blockchain-in-healthcare-market>.

Similarly, according to Precedence Research, The U.S. blockchain industry is expected to grow at a compound annual growth rate (CAGR) of 35.33%, from 2.88 billion in 2024 to 59.32 billion by 2034 (Figure 29). These remarkable growth rates demonstrate the industry's faith in blockchain's ability to transform biotechnology via several interrelated channels (Blockchain in Healthcare Market Size to Hit USD 193.43 Bn by 2034, 2025).

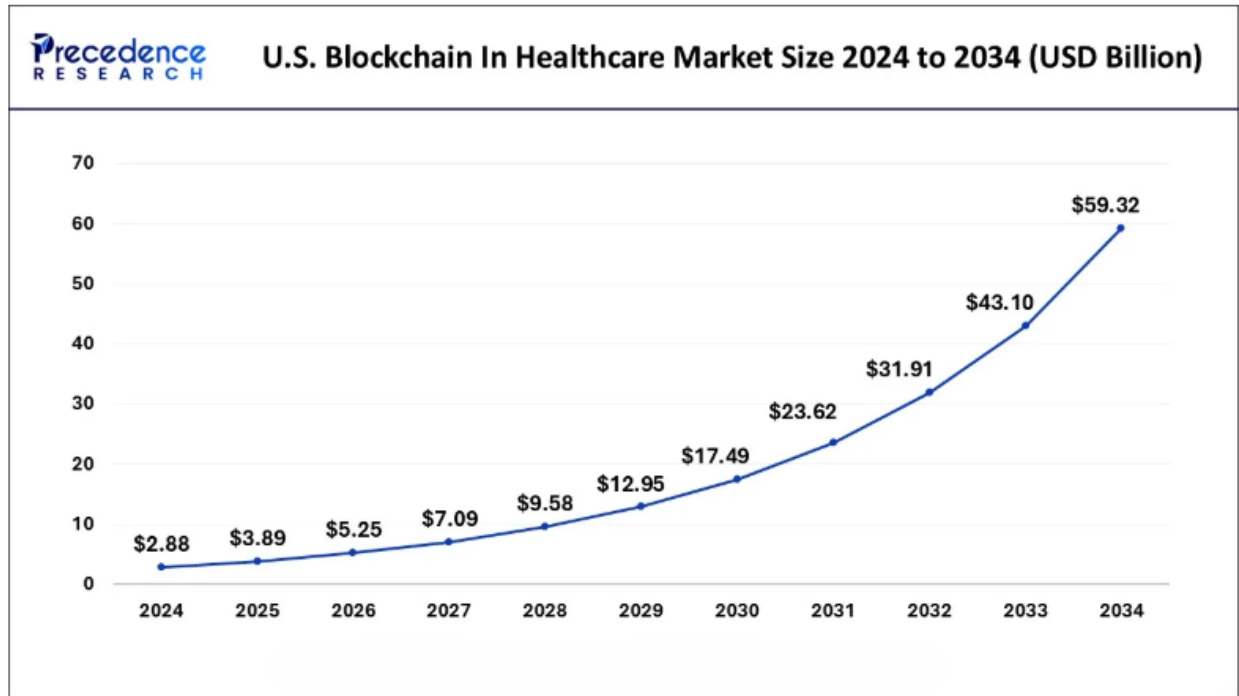


Figure 29: Exponential Growth Trajectory: U.S. Blockchain in Healthcare Market Projected to Reach \$59.32 Billion by 2034 (Blockchain in Healthcare Market Size to Hit USD 193.43 Bn by 2034, 2025), Retrieved June 4, 2025, from <https://www.precedenceresearch.com/blockchain-in-healthcare-market>.

Blockchain will gradually evolve from current applications in healthcare records toward more sophisticated implementations, including direct applications in fundamental biological research such as modeling cancer evolution and implementing smart contracts for biological Boolean logic gates. Blockchain integration with biometric data via NFT frameworks is an exciting avenue that will improve privacy protection while allowing people to retain ownership and control over their biological data. It is anticipated that this development will result in more fair digital health ecosystems with long-term business models for moral data exchange (Tišma & Škrtić, 2023).

Additionally, blockchain's integration with AI and ML will speed up applications in the biomanufacturing, bioenergy, and bio-agriculture sectors, allowing for previously unheard-of levels of traceability and transparency across biotechnology supply chains. With a 43% revenue share as of 2024, North America now leads the healthcare blockchain market, but Asia Pacific is predicted to experience rapid expansion in the years to come. The decentralized architecture of BCT will pose a growing threat to single-entity traditional information ecosystems as it develops, encouraging cooperative research settings where open innovation is permitted but intellectual

property is safely protected (Blockchain in Healthcare Market Size to Hit USD 193.43 Bn by 2034, 2025).

With significant industry growth forecasts, BCT in environmental and agri-food biotechnology provides a nexus of digital innovation and biological sciences. The market for blockchain in agriculture and food supply chains is anticipated to increase at an impressive CAGR of 48.3%, from 0.84 billion in 2025 to 4.04 billion by 2029 (Blockchain in Agriculture and Food Supply Chain Market Report 2025, 2025). whereas the environmental blockchain market for sustainable supply chains was estimated to be worth \$827.6 million in 2024 and was expected to grow at a compound annual growth rate of 35.1% until 2030 (Blockchain for Sustainable Supply Chains Market Size, 2025-2034, 2025). This growth is driven by blockchain's transformative applications in biotechnology, including secure genetic resource management, bioengineering verification, and agricultural biotechnology tracking (Samoggia et al., 2025).

Real-world applications are already shown promise, with improved traceability systems offering transparency from development to consumption and smart contracts facilitating transactions between biotechnology supply chain participants (Chiaraluce et al., 2024). Furthermore, BCT is helping to solve critical industrial issues including preventing fraud in expensive biotechnology products and simplifying regulatory compliance in some jurisdictions. The technology's decentralized architecture enables new cooperative research settings as it develops, allowing biotechnology data to be safely exchanged while safeguarding intellectual property. This will result in more transparent and sustainable biological supply chains from lab to customer (Mulligan et al., 2024).

6. CONCLUSION

This comprehensive bibliometric analysis of BCT in biotechnology has revealed significant insights into the evolution, adoption patterns, and future trajectory of this transformative integration. Several important findings are drawn from a methodical investigation of case studies, citation network analysis, keyword co-occurrence mapping, and publishing patterns in a variety of biotechnology disciplines.

The study clearly shows that BCT has advanced from a theoretical idea to a workable solution that tackles important biotechnological issues. Blockchain's adaptable role in enabling safe,

decentralized, and transparent systems across the biotechnology value chain is demonstrated by our keyword co-occurrence maps across environmental biotechnology, genetics, medical biotechnology, marine biotechnology, agriculture and food biotechnology, and pharmaceutical applications. The general trajectory shows rapid integration, even while implementation maturity varies by sector, with medical and agricultural applications seeing more advanced acceptance compared to developing domains like marine biotechnology.

The steady convergence of blockchain with related technologies is an important discovery. According to the co-occurrence analysis, blockchain rarely functions independently, rather, it is a component of a technological ecosystem that also incorporates big data analytics, the Internet of Things, and artificial intelligence (AI). Companies like Carbios, JBS, and Merck & Co. have implemented blockchain solutions that use these complementary technologies to address complex challenges in plastic recycling, livestock traceability, and pharmaceutical supply chain security, respectively. These case studies highlight this technological synergy.

With some countries exhibiting leadership in particular biotechnology domains, the nation co-citation analysis reveals the establishment of unique research clusters and collaborative networks. The disparities in sector interests, technology infrastructure, and regulatory frameworks that impact blockchain adoption are reflected in the global distribution of research effort. According to the report, global cooperation is speeding up efforts at standardization and knowledge transfer, both of which are essential for tackling the cross-border character of biotechnology supply chains.

Additionally, our study points up several enduring obstacles to the broad use of blockchain in biotechnology. These include the requirement for industry-wide standards, legislative ambiguities across many jurisdictions, integration challenges with current biotechnological infrastructures, and technical constraints about scalability and energy consumption. The analyzed case studies offer important insights into how pioneering companies are getting beyond these obstacles with unique consensus procedures catered to biotechnology applications, strategic alliances, and phased implementation strategies.

From a practical perspective, this research offers several implications for stakeholders in the biotechnology ecosystem. The results offer industry practitioners a path for implementing blockchain, identifying both potential dangers and successful use cases. The study emphasizes for policymakers the necessity of flexible regulatory frameworks that strike a balance between

innovation and biotechnology-specific ethical issues. Bibliometric analysis helps researchers find intriguing research gaps and new issues that need more study.

Looking forward, several trends are likely to shape the future integration of blockchain in biotechnology. First, the existing scalability and energy efficiency constraints will be addressed by the creation of customized blockchain architectures tailored for biotechnological applications. Second, adoption will speed up if industry-specific consensus procedures that take into account the particular needs of biotechnological processes arise. Third, worldwide standardization initiatives and more transparent regulations will lower implementation obstacles. Last but not least, as blockchain continues to converge with AI, IoT, and other cutting-edge technologies, more complex applications in fields like genetic resource management, sustainable bioprocessing, and personalized treatment will become possible.

By offering a thorough mapping of the intellectual ecosystem, identifying important research clusters, and highlighting workable implementation options, this study adds to the expanding body of knowledge on blockchain applications in biotechnology. This thesis provides a comprehensive knowledge of how BCT is changing biotechnology processes and opening up new avenues for innovation by combining insights from bibliometric analysis and real-world case studies.

In conclusion, BCT represents a paradigm shift in how biotechnological data, processes, and products are managed, verified, and secured. Blockchain is changing from a supporting technology to a key enabler of trust, transparency, and efficiency in biotechnology, even though there are still obstacles to overcome. Blockchain will provide the digital foundation for a new generation of biotechnology innovations that are more secure, transparent, and ethically governed as adoption speeds up and technological capabilities advance. Decentralized, data-centric, and technologically linked systems will progressively define the biotechnology industry in the future. BCT will be essential to maintaining integrity, traceability, and trust along the supply chain.

6.1. Future Prospects and Trends in Biotechnology with Blockchain

BCT and biotechnology are combining to create new opportunities in the fields of cyber-biosecurity, drug development, genomics, and healthcare. Research shows how blockchain can accelerate clinical trials and drug discovery by facilitating safe data sharing and using smart contracts to automate procedures (Abbas et al., 2020). In pharmaceutical supply chains, blockchain ensures provenance and combats counterfeit drugs: WHO estimates that between 10 and 30 percent

of medications in low- and middle-income countries are fake, costing the global pharmaceutical sector up to \$200 billion annually (Mohindra et al., 2024). Over a million deaths are caused by counterfeit medications each year, mostly in Asia and Africa. Pilots have demonstrated that implementing blockchain-based traceability systems reduces counterfeit incidences by around 30 to 50%, while QR-code authentication reduces verification time from 48 hours to less than 1 second (Gomasta et al., 2023). Surveys reveal that 83% of pharmaceutical and life-science stakeholders intend to adopt blockchain within five years, with 68% citing supply chain security as its primary benefit (Kumarswamy & Sampigerayappa, 2024). Systematic assessments also highlight how blockchain's immutable ledgers and smart contracts may boost stakeholders trust while lowering transaction costs and increasing transparency (Hosseini Bamakan et al., 2021).

BCT in genomics gives people decentralized ownership over private genetic information, promoting moral, cooperative tailored healthcare. Its tamper-resistant architecture also aids in protecting biological research data from modification in the context of cyber-biosecurity (Blockchain in Genomics Market Size, Growth, Trends, Report 2032, 2025). Also, blockchain-enabled models like Decentralized Autonomous Organization (DAOs) democratize funding for biotech R&D. In genomics, platforms like ConsentChain and EncrypGen demonstrate secure, consent-aware data sharing and marketplace models that compensate individuals for their genomic data (Albalwy et al., 2021).

The decentralized, immutable nature of BCT significantly improves cyber-biosecurity by preventing tampering with critical biological datasets, these developments should be amplified through integration with other cutting-edge technologies:

- **Blockchain and IoT:** enable automated quality control in biomanufacturing and biological sample traceability by enabling real-time, remote monitoring of bioprocess sensor data (Cheikhrouhou et al., 2023).
- **Blockchain and AI:** improves predictive modeling for medication development and healthcare analytics by protecting private biotech datasets for federated learning frameworks like PredictChain and ModelChain (Pisano et al., 2023).
- **Blockchain and Genomics Platforms:** such as Nebula Genomics, establish data marketplaces that are in line with ethical standards, offer clear consent procedures, and provide incentives for individual reward (Albalwy et al., 2021).

Blockchain makes it possible for IoT to track the movement of genome-edited seeds to harvested produce, enhancing food safety and supply-chain transparency in the agri-food and environmental biotech industries. Regional, circular bioeconomy supply chains are advanced by sustainably oriented frameworks, and research validates blockchain's function in closed-loop resource flows and green industrial symbiosis (Holden et al., 2023). It is projected that future blockchain applications combined with biotechnology will advance global development and support the Sustainable Development Goals of affordable and clean energy (SDG 7), climate action (SDG 13), and good health and well-being (SDG 3) (Shukla et al., 2024).

Stakeholder adoption, regulatory compliance, scalability, and interoperability issues still exist, but interdisciplinary cooperation across technical and policy domains can fully realize blockchain's potential to revolutionize biotech, agriculture, and environmental sustainability on a worldwide scale (Loy et al., 2022).

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