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ANALYSING THE POTENTIAL OF BLOCKCHAIN TECHNOLOGY TO OVERCOME CO_2 EMISSIONS TRACEABILITY CHALLENGES IN FOOD PRODUCTION SUPPLY CHAINS.

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Abstract

This thesis investigates the potential of blockchain technology to address CO_2 emissions traceability challenges in food production supply chains, aiming to enhance transparency, regulatory compliance, and accountability under evolving EU frameworks like the Corporate Sustainability Reporting Directive. Combining insights from a literature review and expert interviews, the study identifies adoption challenges, including financial barriers, regulatory ambiguities, and stakeholder resistance. The research provides actionable recommendations for companies, policymakers, and blockchain technology developers, illustrating a pathway to leverage blockchain's potential in advancing sustainability within the food production industry.

Keywords

CO2 emissions | Traceability | Blockchain Technology | Sustainability Compliance | IoT Systems | CO2 Emission Traceability | Food Production | Supply Chain

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List of abbreviations

Abbreviation	**Definition**
CO_2	Carbon dioxide
CSDDD	Corporate Sustainability Due Diligence Directive
CSRD	Corporate Sustainability Reporting Directive
EDGAR	Emissions Database for Global Atmospheric Research
ERFRAG	European Financial Reporting Advisory Group
ESG	Environmental, Social, Governance
EU	European Union
GHG	Greenhouse Gas
GDPR	General Data Protection Regulation
IoT	Internet of Things
NFC	Near-field communication
ISO	International Standards Organisation
NGO	Non-Governmental Organization
PAS2050	Publicly Available Specification 2050: Specification for the assessment of the life cycle.
PoW	Proof of Work: consensus mechanism to verify Bitcoin transactions and add the following block to the Blockchain

1 Introduction

"We are the first generation to feel the effect of climate change and the last generation who can do something about it." – Barack Obama, 2014

The impacts of climate change are becoming increasingly evident and severe, characterized by intensified droughts, floods, and extreme heatwaves that jeopardize agricultural productivity, with projections suggesting further exacerbation by 2030 (Calicioglu et al. 2019). These phenomena pose significant threats to ecosystems, biodiversity, as well as human livelihoods and are escalating in intensity, primarily driven by greenhouse gas (GHG) emissions from human activities (Lintukangas et al. 2022). Among these emissions, carbon dioxide (CO_2) constitutes approximately 79.7%. Notably, the food production sector alone accounts for 37% of global GHG emissions, with CO_2 emissions representing over half of this contribution Schulman et al. 2021. As the global population is projected to rise to 9.7 billion by 2050, the need for sustainable agricultural practices has become critical (UN 2023). Addressing these challenges is further complicated by the intricate supply chains in the food industry, encompassing farming, processing, packaging, and distribution, which hinder transparency and accountability in emissions reporting (Ritchie and Roser 2024).

Recognizing the urgent need to address climate change, the European Union (EU) has set ambitious climate targets through initiatives like the European Green Deal, aiming for climate neutrality by 2050. Building on these objectives, the CSRD, effective January 2024, requires large companies to disclose comprehensive Environmental, Social, and Governance data. This includes Scope 1 emissions, defined as 'direct emissions from owned or controlled sources,' Scope 2 emissions from 'the generation of purchased energy,' and Scope 3 emissions encompassing 'the value chain of the reporting company,' along with disclosures on climate risks, emissions, and resource utilization (Corporate Sustainability Reporting 2024). CSRD applies to large companies meeting specific criteria, including those with over 250 employees,

€40 million in turnover, or €20 million in total assets, with phased implementation for smaller publicly listed firms and non-EU entities by 2028, holding companies accountable for their environmental impacts and supporting the EU's goal of climate neutrality by 2050 (Corporate Sustainability Reporting 2024). However, the tracking and reporting of CO_2 emissions in complex food production supply chains often lack the granularity and reliability needed for comprehensive assessments due to data inconsistencies (Tubiello et al. 2021). The absence of standardized measurement methods further impedes accuracy, particularly for Scope 3 emissions, indirect emissions from value chain activities, which are critical for a complete account of a company's carbon footprint (Ritchie and Roser 2024).

These complexities call for innovative solutions to improve CO_2 emission tracking and to ensure transparent, consistent reporting across supply chains. Therefore, this thesis investigates how blockchain technology can address CO_2 emissions traceability challenges in the food production industry. Combining insights from literature and primary research, it evaluates blockchain's potential, identifies adoption barriers, and provides actionable recommendations for policymakers, companies, and blockchain technology providers.

1.1 Problem definition

CO_2 traceability presents significant challenges in complex food supply chains, where emissions data across Scope 1, 2, and 3 often lack transparency and consistency. Traditional systems such as paper-based documentation fail to provide reliable granular insights, hindering efficient, accurate, and accountable emissions management. Evolving EU sustainability regulations further amplify the urgency for enhanced tracking solutions to ensure transparency and compliance.

1.2 Research Objective and Research Question

This research aims to analyse the potential of blockchain technology in addressing CO_2 emissions traceability challenges and enabling compliance with sustainability regulations in food production supply chains. Guided by the research question, "How can blockchain technology address CO_2 emissions traceability challenges within food production supply chains to enhance transparency, accountability, and sustainability?" the study examines blockchain's capabilities in traceability, its impact on regulatory compliance, and the practical implementation challenges. The study contributes to understanding blockchain's role in advancing sustainability and offers a forward-looking perspective on its application across sectors, focussing on the food production industry.

2 Literature Review

This literature review explores the importance of CO_2 traceability amid rising regulatory and stakeholder demands and examines blockchain technology's potential to enhance transparency, compliance, and accountability in emissions management.

2.1 The Growing Importance and Challenges of CO_2 Traceability

Traceability, as defined by the General Food Law Regulation, refers to the "ability to trace and follow food, feed, and ingredients through all stages of production, processing and distribution" (Food Law General Requirements 2024). In the context of CO_2 emissions, traceability is becoming increasingly critical as organizations face mounting regulatory pressure and stakeholder demands to reduce their environmental impact. Das and Jharkharia (2018) highlight carbon governance as crucial to driving low-carbon practices and reducing corporate footprints. Similarly, Watari et al. (2021) underscore institutional mechanisms, resource governance, and circular economy practices as critical for enhancing carbon transparency in global supply chains.

2.1.1 Drivers of CO_2 Traceability: Stakeholders and Regulation

Stakeholder influence is a powerful driver of carbon traceability. External actors, including NGOs, investors, and consumers, increasingly demand robust decarbonization strategies. Ceesay (2020) highlight the influence of NGOs in holding companies accountable for their environmental impact, while Seroka-Stolka (2023) demonstrates that more substantial stakeholder pressure correlates with more advanced carbon reduction strategies. This pressure not only drives companies toward transparency but also improves their CO_2-related performance, reinforcing the importance of stakeholder engagement in sustainability efforts.

Regulatory developments within the European Union also intensify the need for carbon traceability. The European Green Deal, approved in 2020, aims to make the EU climate-neutral by 2050, with an intermediate target of reducing net greenhouse gas (GHG) emissions by 55% by 2030 compared to 1990 levels. These ambitious targets, stipulated in the EU Climate Law, place substantial pressure on companies to align with sustainability objectives. Another cornerstone of the EU's regulatory framework is the CSRD, which mandates companies to measure and disclose their environmental, social, and governance (ESG) impacts, thereby promoting transparency, comparability, and accountability across industries (European Commission 2024). High-profile legal cases, such as the initial ruling by the District Court of The Hague requiring Royal Dutch Shell to reduce CO_2 emissions by 45% by 2030, exemplify the integration of international climate standards into domestic legal frameworks. Although overturned on appeal in November 2024, this landmark case remains globally significant as the first to impose such a mandate on a private corporation and highlights the increasing regulatory and societal pressure on companies to disclose and mitigate their emissions, as well as the growing momentum toward legally binding climate accountability (Kaminski 2024).

2.1.2 Challenges in Tracking CO_2 Emissions

Achieving comprehensive CO_2 traceability is particularly challenging in the food production sector due to its complex supply chains. These involve multiple stages, from farming, production, post-harvesting, processing, packaging, transportation and distribution, retail, consumer purchase, waste management, each contributing varied emissions. The diversity of stakeholders, from smallholders to large corporations, complicates data collection and consistency. Additionally, emissions stem from diverse sources, including livestock, crop production, land-use changes, and supply chain logistics. This complexity is exacerbated by the lack of universally accepted and defined standards and procedures to track and report CO_2 emissions across supply chains, leading to suppliers using varying methods, metrics, and tools to calculate emissions. This frequently results in inconsistent or incomplete data. Current methodologies, such as expenditure-based modelling, rely on industry-average emission factors, which fail to account for company-specific profiles. For example, GHG emissions for similar products can vary by up to 50 times due to factors like soil carbon variability and land-use practices (Ouatahar et al. 2021), underscoring the need for emission calculations that are based on actual performance and processes rather than generalized industry averages.

The predominance of Scope 3 emissions compounds these challenges, as they often represent the largest share of a company's GHG output, significantly increasing complexity. Between 1995 and 2015, global Scope 3 emissions rose by 84%, intensifying the difficulty of managing indirect emissions across supply chains (Hertwich and Wood 2018). These emissions rely heavily on supplier data, which is frequently inaccessible, inconsistent, and incomplete. Such data deficiencies, driven by a lack of transparency and verification, impede organizations' ability to pinpoint emission hotspots or develop targeted reduction strategies.

2.1.3 Limitations of current tools and frameworks

Existing tools and frameworks provide structure for emissions reporting but remain insufficient for addressing the complexities of supply chains. The GHG Protocol is widely adopted for GHG measurement, covering Scope 1, Scope 2, and Scope 3 emissions and includes both upstream and downstream emissions (GHG Protocol 2013)[1]. However, tracking Scope 3 is challenging, as it relies on data from suppliers, which may be inconsistent (PricewaterhouseCoopers 2024).

1 Appendix 1: Overview of GHG Protocol scopes and emissions across the value chain (Liu, Wu, and Chau 2023)

Furthermore, in food production, where emissions are emitted via a broad range from land use to distribution, the Emissions Database for Global Atmospheric Research (EDGAR-FOOD) is vital as it provides GHG data for over 220 countries and tracks emissions throughout the food system (EDGAR 2024). However, EDGAR-FOOD does not fully capture Scope 3 emissions and relies on average emissions factors, limiting its application to detailed, supply chain-specific analysis.

Another tool for evaluating the environmental impact of organizations is the carbon footprint calculation, which quantifies total greenhouse gas emissions. Approaches such as Life-Cycle Assessment (LCA) and PAS2050, which quantify emissions by analysing inputs, outputs, and processes across a product's life cycle, measure emissions in CO_2; however, inconsistencies in data collection and scope complicate comparisons across entities (Fenner et al. 2018). These tools rely on industry-average data or expenditure-based modelling, which, while broadly applicable, fail to capture the heterogeneity of emissions across specific products and processes, resulting in inconsistent and unreliable reporting outcomes. Underscoring the challenges of achieving accuracy and comparability in emissions reporting, an empirical study by Harangozo et al. (2017) revealed that while most tested calculators effectively accounted for Scope 1 emissions, straightforward to identify compared to the complexity of Scope 3 emissions, only one in eight carbon calculators fully adhered to GHG Protocol guidelines.

2.1.4 Regulatory Challenges and Resource Demands

The regulatory landscape introduces additional complexities as companies face increasing pressure to comply with stringent reporting requirements under the CSRD. While these requirements aim to enhance transparency and accountability by mandating the disclosure of ESG metrics, they also place operational demands on companies, necessitating investments in information technology infrastructure, personnel training, and data collection systems to ensure accurate data management, effective operational monitoring, and regulatory compliance (Odobaša and Marošević 2023).

Furthermore, regulatory ambiguity exacerbates the reluctance of many organizations to invest in compliance tools or advanced technologies. Shifts in political and economic landscapes, such as geopolitical tensions, inflation, and the reversal of climate policies in certain jurisdictions, have created an environment of uncertainty. This global polycrisis leaves some organizations hesitant to adopt sustainability measures, fearing that evolving regulations may render their investments obsolete (Carlin 2024). Such uncertainty partially undermines proactive engagement with sustainability goals, delaying progress toward achieving compliance and reducing carbon footprints.

In conclusion, while the importance of CO_2 traceability continues to grow due to regulatory and stakeholder demands, significant challenges remain in achieving comprehensive and accurate emissions reporting. Identifying these barriers will require investment in robust data collection, enhanced methodologies, and the alignment of standards to foster transparency.

2.2 Blockchain Technology

Blockchain technology, a decentralized and distributed ledger system, an information storage framework in which data is replicated across multiple network participants rather than being maintained by a single central authority, records changes in data securely and transparently in linked blocks (Lv et al. 2023). Key features such as decentralization, immutability, transparency, and traceability distinguish blockchain from traditional data storage systems, enabling participants with real-time access to accountable and verified information, which is essential for the effective management of complex supply chains (Saha et al. 2022; Tabatabaei et al. 2023). As information is digitally linked to each product, creating a verifiable record of its provenance, compliance, authenticity, and quality, it accompanies the product throughout the supply chain, ensuring accessibility of the data for stakeholders (Bumblauskas et al. 2019).

2.2.1 Blockchain's Role in Food Supply Chains

"By 2025, 20% of the top 10 global grocers by revenue will be using blockchain for food safety and traceability to create visibility to production" (Egham 2019), underscoring blockchains significant potential to improve transparency and information sharing in supply chains (Tabatabaei et al. 2023). Additionally, Blockchain systems securely document transactions and create shared access for stakeholders, enabling the tracking of food products from "farm to fork," meaning from their origin at the farm to their final destination on the consumer's plate (Purnhagen et al. 2021). This transparency supports compliance with sustainability standards by capturing detailed data on agricultural practices, transportation conditions, packaging, and storage (Astill et al. 2019). Notable systems like IBM Food Trust uses blockchain to connect producers, processors, retailers by securely recording and sharing data on product origin, handling, and movement, with an additional suite enabling the capture and exchange of product-level emissions data chains (IBM Food Trust n.d.).

2.2.2 Blockchain's Applications in Carbon Emission Management

Blockchain offers a promising solution for enhancing transparency and accountability in CO_2 emissions management, particularly in carbon offsetting, a practice of compensating for emissions by funding an equivalent carbon dioxide saving elsewhere (Saraji and Borowczak 2022; Aggarwal 2024). Blockchain-based carbon trading enables the secure exchange of carbon credits, digital certificates representing verified GHG reductions, stored as tokens, unique digital assets on the blockchain for easy tracking, trading, and verification (Kim and Huh 2020). Blockchain's decentralized structure enhances transparency in tracking the origination, ownership, and retirement of these carbon credits, reducing fraud risks and fostering trust in carbon markets. Platforms like VeChain integrate IoT devices such as sensors to monitor real-time emissions, immutably recording energy and fuel consumption data on the blockchain (VeChain 2024). For instance, China's largest wine importer uses VeChain's blockchain and NFC chips, allowing consumers to verify authenticity and trace origins

(VeChainInsider 2020). These systems enhance regulatory compliance and bolster credibility in sustainability reporting by providing stakeholders with reliable, auditable data.

2.2.3 Enhanced Traceability and Emission Monitoring

Integrating blockchain with IoT offers the potential for enhancing CO_2 traceability, enabling real-time emissions monitoring at every supply chain stage. Automated sensors can gather data on energy and fuel use, transmitting it to the blockchain for validation, ensuring accurate, accessible emissions information (Wang et al. 2020). Furthermore, smart contracts within blockchain systems facilitate emissions tracking and compliance, triggering alerts or corrective actions if emissions exceed set limits. This capability aids companies in meeting EU standards, such as the CSRD, by enabling automated, transparent reporting and enabling stakeholders to verify compliance (European Commission 2024). EY OpsChain ESG serves as a practical example of a blockchain-based solution that provides organizations with a verifiable view of their CO_2 emissions by tokenizing emissions and carbon credits. The tool enhances transparency and ensures independently verifiable, immutable data; however, its effectiveness relies on the accuracy of input data, posing a challenge for companies to collect precise CO_2 data across their operations (Ernst & Young Global Limited 2024).

2.2.4 Challenges and Considerations

While blockchain holds promise for transforming emissions traceability, challenges remain. Blockchain faces scalability issues, as increased transaction volumes slow consensus mechanisms compared to centralized systems. Data storage constraints often require off-chain solutions, potentially compromising security (Wu et al. 2019). These technical limitations require further innovation to ensure that blockchain systems can handle the high transaction volumes typical of food supply chains, arising from the numerous steps in the "farm to fork" process, each generating multiple data points and transactions (Mao et al. 2018). Organizational challenges encompass the expenses of implementing and maintaining blockchain infrastructure, coupled with the necessity for advanced digital skills to effectively manage and utilize these systems. Especially smaller companies or those with limited budgets might find these costs prohibitive, if they do not immediately see a return on investment (Longo, Nicoletti, and Padovano 2019). Lastly, regulatory challenges, particularly in data privacy, require companies to navigate complex compliance landscapes, especially as data is shared across multiple jurisdictions (Alonso et al. 2019).

The environmental impact of blockchain technology also represents a significant challenge due to its substantial energy consumption. Blockchain systems relying on the Proof-of-Work algorithm, such as Bitcoin require extensive power, resulting in enormous energy demands and a large carbon footprint as in 2022 alone, blockchain technology consumed over 1.3 billion kWh globally (Taherdoostet 2024; Bauk 2023). Bitcoin exemplifies this issue, with its annual carbon footprint reaching 98.10 Mt CO_2, comparable to that of Qatar and with a single transaction producing as much CO_2 as 1,185,234 VISA transactions (Digiconomist 2024).

3 Methodology

3.1 Research Design

The research methodology for this dissertation is designed to meticulously investigate the research question: "To what extent can blockchain technology address CO_2 emissions traceability challenges and enable compliance with sustainability regulations in food production supply chains? It encompasses both secondary and primary research methodologies to ensure a comprehensive understanding of the subject matter.

3.1.1 Data Collection Method

Secondary Research:

The secondary research involved a systematic review of academic literature, reports, and case studies from databases like ResearchGate and Google Scholar, using terms such as "blockchain," "CO_2 emissions," "traceability," "CSRD," and "food production." The literature review focused on the current state of CO_2 emissions traceability and investigated blockchain technology applications in food supply chains and carbon emission tracing helping to establish the study's theoretical foundation and identifying gaps explored in the primary research.

Primary Research:

The core of the primary research was based on semi-structured interviews, designed to facilitate an in-depth exploration of expert perspectives. A total of 14 interviews were conducted, encompassing two groups: seven blockchain experts and seven sustainability professionals[2]. Participants were purposively sampled, requiring a minimum of three years of professional experience in their respective fields related to blockchain, regulatory compliance, sustainability reporting, and food production. The interview process was structured into two distinct streams to ensure a comprehensive investigation of the research topics. The first stream focused on blockchain experts who were presented with six standardized questions to gather foundational insights into blockchain technology[3]. The second stream targeted sustainability experts with substantial work experience in sustainability who were asked five standardized questions[4]. In addition, all interviewees were asked three to five tailored questions aligning with each participant's professional experience, covering topics such as IoT technology, compliance, CO_2 emission tokenization, CO_2 emissions in the agricultural sector. This dual approach of standardized and individualized questioning ensured the collection of nuanced and diverse insights[5]. All interviews were conducted virtually with prior consent for recording, lasting 45 to 60 minutes each.

3.2 Data Analysis

The data analysis for this study was conducted using a thematic analysis, reporting patterns within qualitative data. This approach was chosen to ensure a systematic and comprehensive

[2] Appendix 2: Interviewee Background Information
[3] Appendix 3: Standardized Interview Questions for Blockchain Experts
[4] Appendix 4: Standardized Interview Questions for Sustainability Experts
[5] Appendix 5: Interview Transcript of Interview 2

interpretation of the interview data. To structure the analysis, a coding strategy was applied using the software DELVE, which involved generating 28 codes inductively from the data, capturing key elements and patterns. These codes were then grouped into seven overarching categories, which emerged as central thematic areas[6] and deriving core insight themes. To ensure the robustness of the analysis, the key themes identified were systematically compared with findings from the literature review, allowing for the identification of overlaps, reinforcing the validity of the themes, as well as gaps, and highlighting areas where the findings offered novel contributions to the field.

3.3 Limitations

This study offers valuable insights into the opportunities and challenges of blockchain technology in addressing CO_2 emissions traceability. However, key limitations underscore the need for further research. While the diverse backgrounds of 14 interviewees enriched the findings, the sample size may not fully represent all stakeholders in the food production, sustainability, or blockchain industries. The study's focus on food production also limits the generalizability of its findings to other sectors with distinct emissions tracking challenges.

Although the integration of blockchain with IoT was identified as critical, the research lacked detailed technical guidance for implementation. Additionally, the evolving regulatory landscape, such as the CSRD, may influence the long-term relevance of the findings. Blockchain's immutability, though beneficial, may conflict with data privacy regulations, yet strategies for balancing transparency and compliance were not explored. Furthermore, while cost was highlighted as a barrier to adoption, the study did not assess economic feasibility or broader stakeholder attitudes, including consumer perceptions. Future research should expand participant diversity, explore additional technologies, and provide comprehensive economic

[6] Appendix 6: Coding Categories and Codes

and technical analyses to enhance understanding of blockchain's potential for improving CO_2 traceability.

4 Expert Interview Analysis

This section presents the key results of interviews conducted with sustainability and blockchain experts. The primary research aims to identify key challenges in CO_2 emissions tracking, assess the potential of blockchain technology to address these challenges, explore barriers to its adoption, and evaluate future directions for blockchain's role in traceability initiatives.

4.1 Current Challenges in CO_2 Emission Tracking

The interviews revealed a consensus among sustainability experts that tracking CO_2 emissions remains labour-intensive, complicating routine operations. A key challenge highlighted was the reliance on estimations and manual data collection, exacerbated by the lack of granular supplier data, leading to compromises in the accuracy and consistency of emissions reporting. As Interviewee 9 stated, "(...) we use the monetary value as a proxy, which is the worst you can do, but it's what we have." This also aligns with the observation of Interviewee 13 that only 5% of emissions data comes directly from suppliers, while 80% rely on quantity-based factors and 15% on financial data.

A significant challenge arising from the complexity of supply chains is the accurate tracking of Scope 3 emissions, which often rely on supplier estimates or generalized emission factors rather than specific, measured values, limiting the ability to identify hotspots or implement reduction strategies. Interviewee 14 noted, "Scope 3 data is still a problem. It's not updated. It's still very restricted," while Interviewee 7 emphasized that Scope 3 emissions, constituting the largest share, are particularly difficult to track and often calculated using outdated data. Complementing this, challenges such as the manual data entry and verification were highlighted, as they are being described by interviewees as error-prone processes that lack real-time accountability. Supplementary, blockchain and sustainability experts stressed the urgent need for standardized, automated tools to streamline data collection to improve accuracy.

In addition to technical obstacles, compliance with EU regulations has driven the demand for transparency in CO_2 emissions reporting. The lack of standardized data collection methods across regions exacerbates the challenges of achieving EU-compliant reporting. This is especially challenging in the food production sector, where fragmented systems hinder the accurate data collection needed for EU compliance.

Furthermore, Interviewee 13 observed that many companies delay investments in compliance tools due to ongoing regulatory uncertainties, explaining, “The CSRD and related regulations are so new that even sustainability and compliance experts are unsure about the development and the finalization of these laws. Companies are on hold when it comes to investments because they fear needing to change processes once the regulations are clearer”.

Reviewing the industry-specific burdens in CO_2 emission tracking, interviewee 14 emphasized significant methodological challenges in CO_2 emission tracking for carbon credits, particularly for crops, while also pointing out a critical regulatory gap. EU regulations do not currently mandate or effectively support accounting for carbon sequestration – the process of capturing and storing atmospheric CO_2, – in agricultural practices, hindering farmers from fully leveraging their contributions to carbon reduction. As the interviewee explained, “We cannot only state what our emissions are; we must state also what is our positive impact in the system. But there are not enough certified methodologies that actually help farmers state that we are carbon negative.” This gap is further exacerbated by the lack of precise mechanisms and tools to help farmers calculate their carbon credits effectively, as well as the significant investments required in tools, methodologies, and expertise to generate them – “The EU regulations do not address carbon sequestration effectively, (…) we need systemic solutions that make it feasible for farmers to benefit from them.” The absence of accessible and standardized methodologies, combined with insufficient regulatory support, poses a significant barrier for farmers to participate equitably in carbon credit markets.

4.2 Blockchain's Potential for CO_2 Traceability and Regulatory Compliance

4.2.1 Transparency and Immutable Records

The interviews underscored blockchain's potential to enhance CO_2 traceability through its decentralized and immutable architecture. By ensuring data integrity and reducing reliance on centralized systems, blockchain addresses inconsistencies in current tracking methods. Interviewee 1 remarked: "You could offer just a transparent and immutable record of those emissions at each stage, enabling real-time data tracking and quick identification of CO_2-heavy processes." Blockchain's capacity for transparent documentation of environmental impacts is valuable for regulatory compliance and stakeholder accountability. As Interviewee 12 stressed, its ability to capture product lifecycles, is particularly relevant in the food production sector, allowing granular traceability across cultivation, processing, and distribution.

4.2.2 Applications of Blockchain for CO_2 Tracking

The interviews identified key blockchain applications for improving CO_2 emissions tracking:

1. Blockchain's ability to trace a product's carbon footprint throughout the supply chain is a key application, enabling accurate verification of sustainability claims by recording emissions data at every stage. As Interviewee 5 noted, "Blockchain provides complete traceability from farm to fork, including emissions data," a critical feature for transparency in food production, regulatory compliance, and consumer trust.

2. The integration of blockchain with Internet of Things (IoT) devices enables real-time emissions tracking. IoT sensors can monitor CO_2-heavy processes and log the data directly onto a blockchain ledger, ensuring secure and immutable records. Interviewee 1 explained, "You can integrate IoT devices with blockchain to enable real-time emission tracking, which helps identify CO_2-heavy processes quickly and take immediate action." This approach minimizes errors and enhances operational responsiveness.

3. Several interviewees identified blockchain-based platforms for managing and trading carbon credits as transformative as they ensure the transparency and traceability of carbon offsets by documenting their lifecycle from issuance to trade. Blockchain-based carbon credit systems build trust and accountability in carbon markets by reducing fraud and double-counting.

4. Interviewees specialized in blockchain applications within the finance sector emphasized the tokenization of carbon credits, which creates digital representations of carbon offsets for trading on blockchain marketplaces, as a particularly promising application. Interviewee 1 noted, "Blockchain can be used for the tokenization of carbon credits to enhance transparency."

4.2.3 Regulatory Compliance and Competitive Advantage

When examining compliance with EU regulations, all interviews with blockchain experts revealed a strong consensus that blockchain technology holds significant potential to support sustainability mandates. Its ability to provide transparent, immutable records of emissions data offers a reliable framework for meeting stringent regulatory requirements. By ensuring that data is both tamper-proof and easily auditable, blockchain can streamline the compliance process and reduce the risks associated with manual reporting errors. Several interviewees highlighted the likelihood of blockchain becoming an integral component of regulatory frameworks in the near future, particularly in relation to certifications such as ISO standards or EU sustainability requirements. As Interviewee 5 noted, "Sooner or later, blockchain will become mandatory as part of EU sustainability certifications, giving early adopters a significant competitive edge." Interviewee 12 further emphasized that proactive blockchain integration could position companies as leaders in sustainability innovation, enhancing their market reputation while ensuring readiness for evolving regulatory landscapes. However, other interviewees argued that the use of blockchain will have an immense problem with data integrity and new upcoming regulations in that matter will make it harder for blockchains to operate, as Interviewee 4 stated: "The immutability of data conflicts with privacy laws that require information to be deleted, which could make blockchain solutions harder to implement as regulations tighten.”

4.3 Challenges in Blockchain Adoption

While blockchain offers transformative potential, its integration is not without challenges. The subsequent section explores the technological, financial, legal, and cultural barriers to blockchain adoption that emerged from the interviews.

4.3.1 Technological Complexity and Integration Challenges

A recurring theme in the interviews was the perceived complexity of implementing blockchain solutions. Blockchain integration often requires substantial re-engineering of existing systems, disrupting established workflows and creating resistance among stakeholders. Interviewee 10 emphasized the difficulty of such transitions, stating: “Even changing between one system to another is hard. How about changing the whole technology? You need to re-engineer the whole process”. The lack of expertise within organizations further exacerbates these challenges. Interviewee 10 compared the adoption of blockchain to the early days of the Internet: “Most people working in companies don’t have a clue about blockchain. It’s similar to the Internet in the 2000s—there’s always resistance to change.” This analogy underscores the nascent stage of blockchain adoption and the scepticism surrounding its value, often due to limited understanding and technical expertise among managers and employees.

4.3.2 Cost and Resource Intensity

A key barrier identified was the significant financial and labour costs associated with blockchain implementation. Transitioning to blockchain-based systems requires extensive operational adjustments and reconfiguration of processes, leading to increased resource demands. Interviewee 10 noted: “Integrating blockchain requires companies to re-engineer their processes entirely, which is complex and costly.” The need for specialized technological infrastructure and skilled personnel adds to these costs, making blockchain adoption particularly challenging for small- and medium-sized enterprises with limited resources.

4.3.3 Stakeholder Resistance and Misconceptions

Resistance to change emerged as a critical barrier to blockchain adoption. Stakeholders face challenges in recognizing the value of blockchain technology, which is frequently associated with misconceptions about its nature and applications. Interviewee 6 observed: "The lack of understanding among stakeholders is a significant barrier (…) making adoption challenging in traditional industries like agriculture." Blockchain's association with cryptocurrencies has led to scepticism, as it is frequently linked to speculative bubbles, fraud, and regulatory controversies. Interviewee 8 remarked: "If you do a word cloud with people around, (...) the biggest word that will appear will be cryptocurrencies and scam." Similarly, Interviewee 10 added: "When people think of blockchain, they say Bitcoin. And they think that either it comes with lots of money from good investments or people lose all their money." These deeply rooted perceptions undermine trust and impede the adoption of blockchain technology in industries beyond finance, where its use is increasingly gaining traction.

4.3.4 Regulatory and Compliance Challenges

Blockchain's inherent immutability creates significant challenges in aligning with regulatory frameworks, particularly in jurisdictions with stringent data protection laws. Two interviewees specifically mentioned the conflict between blockchain's design and the European Union's General Data Protection Regulation (GDPR). The GDPR provision, known as the "right to be forgotten", fundamentally conflicts with blockchain's inherent design, preventing recorded data deletion or alteration (GDPR 2017). Interviewee 1 clarified this regulatory misalignment: "Governments need clear regulations for blockchain use. In the EU, data privacy laws like GDPR conflict with blockchain's immutability, where data cannot easily be deleted." This tension further complicates blockchain implementation for companies handling sensitive data as they face uncertainty about how to comply with both technological and legal requirements. Furthermore, Interviewee 13 highlighted regulatory uncertainty and corporate caution in adopting solutions, noting that the EU's rapidly evolving regulatory environment, shaped by frameworks like the CSRD, EU Taxonomy, and upcoming CSDDD, creates hesitation among companies. While these regulations signal a shift towards accountability, unclear timelines and requirements, thus making planning difficult, deterring major investments in new systems or technologies. “Companies don’t know how these regulations will develop in the next few years, and that makes them reluctant to invest” (Interviewee 13). The rapidly evolving regulatory landscape creates a gap between policy developments and businesses' capacity to adapt, prompting a reactive approach as companies wait for more straightforward guidance. Interviewee 13 emphasized the need for policymakers to offer clarity and stability to support confident investment in sustainability initiatives.

To conclude, the interviews highlight pressing challenges and barriers in CO_2 emissions tracking, underscoring blockchain's transformative potential for improving transparency, accuracy, and regulatory compliance in supply chains.

5 Results and Discussion

This chapter identifies key gaps and opportunities in adopting blockchain and advanced technologies for CO_2 emissions tracking[7]. While the literature offers a theoretical foundation, the primary research provides practical insights, emphasizing nuanced barriers and opportunities for blockchain integration in CO_2 traceability.

5.1 Limited Appeal of Advanced Solutions

Both the literature and primary research recognize the potential of integrating blockchain with IoT to enhance CO_2 emissions traceability by enabling real-time data collection, enhanced

[7] Appendix 7: Comparison of Literature Review and Primary Research

accuracy, and automated compliance processes. However, primary research emphasizes critical barriers, not fully addressed in the literature, such as high implementation costs, technical complexities, and operational challenges. This disparity illustrates that theoretical optimism about these technologies fails to account for practical limitations of organizational readiness and financial constraints. Furthermore, while both literature and primary research identify limitations in Scope 3 emissions tracking, the literature focuses on technological solutions without addressing the cultural, operational barriers identified in primary research.

Interviews reveal that current regulatory frameworks allow high-emission companies to conceal emissions using outdated benchmarks, a limitation largely unaddressed in theoretical studies. While the literature assumes that tools like blockchain and IoT will drive systemic change, primary research stresses the need for more vigorous regulatory enforcement to compel action among laggards. Without making tools accessible to all companies and mandating stricter accountability, the transformative potential of blockchain and IoT will remain to sustainability leaders.

5.2 Blockchain's Trust Deficit

Beyond the challenge of costly implementation, both literature and primary research highlight resistance and scepticism toward blockchain, with primary research revealing more profound cultural and psychological barriers. Many stakeholders remain wary of blockchain due to its association with Bitcoin and financial scams, a connection often overlooked in the literature. This scepticism undermines trust and slows adoption. Furthermore, primary research highlighted that stakeholders often feel the need to fully understand blockchain’s technology before trusting it. A key reason for this mistrust could lie in the significant investment required to integrate blockchain. Unlike accessible technologies like AI, which often have free or low-cost tools, blockchain requires significant investment, heightening scrutiny over its adoption. Additionally, trust becomes paramount when businesses are required to upload sensitive data onto the blockchain. The association with cryptocurrencies exacerbates these trust issues and creates a barrier to adoption, leaving us with a key question: Can blockchain realistically achieve mainstream adoption in sustainability without a redefined narrative that builds trust and separates the technology from its controversial cryptocurrency origins? Without a redefined narrative that builds trust and demonstrates practical applications, blockchain risks being confined to niche use cases, overshadowed by its controversial reputation.

5.3 Blockchain's Potential Beyond CO_2 Traceability

While both, the literature and primary research recognize blockchain's ability to ensure data immutability and transparency, the literature emphasizes blockchain as a tool for emission tracking and compliance but provides limited exploration of its broader applications, such as carbon credit systems. Primary research addresses these gaps by emphasizing blockchain's potential in carbon credit systems and the role of carbon sequestration. Blockchain's value is inherently dependent on its integration with other technologies. Primary research highlights its limitations when used in isolation, as secure data storage does not address key issues like data accuracy and granularity. If the data uploaded to the blockchain is outdated or vague, its transparency and immutability offer little benefit. Experts emphasize that blockchain's real value lies in integration with complementary technologies such as IoT, enabling real-time tracking, automated compliance, and detailed documentation across supply chains. These integrations significantly enhance the promptness and accuracy of emissions data, addressing one of the significant challenges in CO_2 traceability. However, this approach also demands higher investments and implementation costs, raising concerns about accessibility for companies with limited resources. Without opportunities to mitigate implementation costs, blockchain risks being an incomplete and expensive solution.

5.4 Regulatory Uncertainty

While the literature frames regulations like the CSRD as critical for promoting sustainability, primary research reveals that their evolving and unclear nature often stalls progress. This uncertainty discourages companies from investing in compliance tools, as even sustainability experts remain unsure about how these laws will solidify. Furthermore, the immutability nature of blockchain data clashes with GDPR, adding complexity to adoption. A significant challenge arises: policymakers' failure to establish consistent and actionable guidelines risks undermining their sustainability objectives. Primary research highlights that reactive companies, already hesitant to improve their emissions tracking, are further disincentivized by this regulatory ambiguity. Instead of pushing for innovation, unclear frameworks allow these companies to continue relying on outdated practices and vague benchmarks. To avoid this stagnation, policymakers must focus on creating clear, consistent regulations that encourage all companies, not just proactive leaders, to invest in accurate emissions-tracking systems. Without stability, these frameworks risk becoming obstacles rather than enablers of progress.

6 Recommendations

This chapter presents recommendations for key stakeholders—companies, policymakers, and blockchain operators—to address challenges identified in this study and leverage blockchain technology to advance CO_2 emissions traceability. The recommendations aim to enhance efficiency, clarify regulatory frameworks, and build of consumers trust in blockchain solutions, bridging the gap between its theoretical potential and practical adoption to support actionable and inclusive sustainability efforts.

6.1 Companies: Enhancing Operational Efficiency and Adoption

Companies should assess their current operational challenges in emissions reporting to navigate the increasing demand for CO_2 transparency and prepare for evolving regulations. As analysed in this study, blockchain technology can offer significant potential for organizations that will eventually be required to disclose Scope 1, 2, and 3 emissions. Proactive exploration of industry-specific use cases, particularly in the food production sector, is essential. This includes conducting pilot programs that integrate blockchain with IoT to enable real-time emissions tracking across farming, processing, and logistics stages, thereby ensuring both long-term compliance and competitive positioning.

Food production companies should also prioritize developing granular metrics for emissions reporting, such as tracking emissions by crop type, or processing methods, to address the characteristics of agricultural emissions, provide actionable insights and improve reporting accuracy, fostering a more precise understanding of emissions sources across the supply chain. Additionally, as primary research highlights financial constraints as a key barrier to adoption, conducting cost-benefit analyses to evaluate the economic viability of blockchain can reveal potential cost savings from automated compliance processes, making adoption more feasible.

6.2 Policymakers: Addressing Regulatory Ambiguity

Regulatory uncertainty around EU directives like the CSRD has been identified as a key deterrent to investment in advanced emission-tracking technologies. Policymakers should provide clear, harmonized standards, actionable frameworks, and consistent timelines to reduce uncertainty. Furthermore, to address the unique challenges of food production, regulators should clarify sector-specific guidelines for emissions tracking, considering the variability in emissions from crop production, and other agricultural activities.

Primary research revealed a divide between proactive companies leveraging advanced tools and reactive companies relying on outdated methods. The latter group often lacks motivation to innovate, preferring to meet minimal compliance requirements. Developing tailored incentives such as tax credits or subsidies would encourage lagging companies to adopt emissions-tracking technologies. These incentives can offset financial and technical challenges, compelling reactive firms to move beyond vague benchmarks and adopt transparent, accurate reporting systems. Furthermore, addressing the lack of support for carbon sequestration in agricultural practices is critical. Policymakers should provide standardized methodologies and financial, technical, and regulatory assistance to enable farmers to quantify and report their sequestration efforts effectively.

6.3 Blockchain Technology Companies: Building Trust and Accessibility

Primary research reveals that blockchain's association with cryptocurrencies and a lack of understanding and trust significantly hinder its adoption in sustainability. To mitigate this, blockchain operators should actively dissociate the technology from cryptocurrencies, emphasizing its applications in enhancing sustainability and CO_2 traceability. Showcasing case studies of successful implementations particularly in the food production sector can build trust and understanding among stakeholders. Furthermore, blockchain operators should also develop platforms tailored to food supply chains, incorporating industry-relevant functionalities and integration with existing agricultural tools, streamlining the adoption by aligning with the operational realities of food production companies. Additionally, operators should enhance accessibility by designing user-friendly interfaces, allowing farmers and other stakeholders to input emissions data without technical expertise. This approach would ensure broader inclusion and more comprehensive data capture.

To exemplify the application of the study's recommendations within the complex food production supply chain, this framework maps the stages from farming to waste management. It aligns the proposed recommendations for companies, policymakers, and blockchain technology operators with specific Scope 1, 2, and 3 emissions sources. By integrating blockchain and IoT technologies, the framework addresses challenges by improving data collection, traceability, and facilitating emissions reporting. The accompanying diagram highlights key emissions across the supply chain, illustrating how blockchain and IoT solutions can be applied to enhance transparency, accountability, and compliance[8].

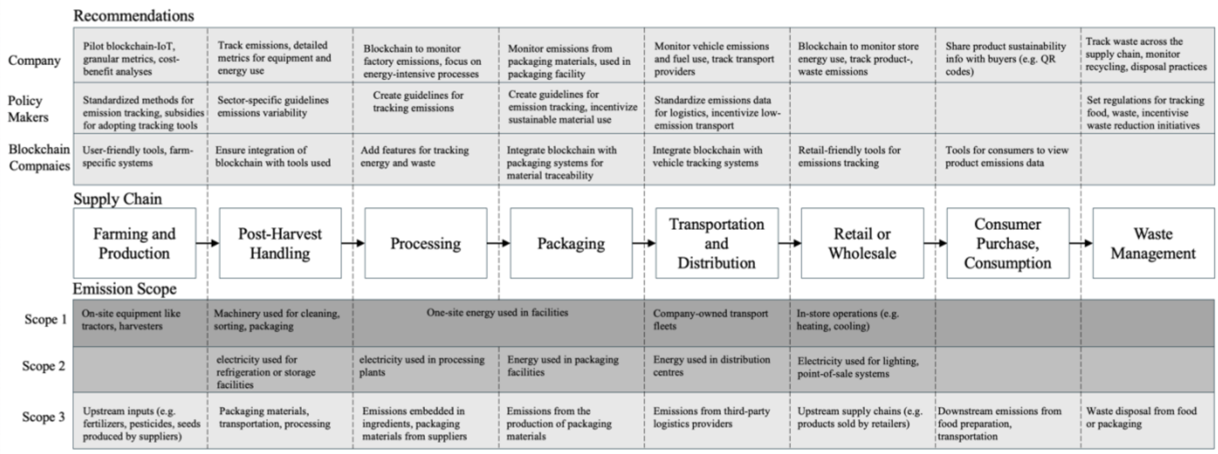

Figure 1: Blockchain Integration in Food Supply Chain Emissions Management (Broich 2024)

7 Conclusion

This study examined how blockchain technology can address CO_2 emissions traceability challenges in food production supply chains. It identifies key barriers, including the complexity of Scope 3 emissions reporting, regulatory ambiguity under the CSRD framework, and stakeholder scepticism. Despite these obstacles, the integration of blockchain with IoT demonstrates potential to enhance transparency, compliance, and traceability, positioning it as a transformative tool for the sector. By bridging theoretical insights with practical applications, this thesis concludes that, while blockchain offers a viable pathway to advancing sustainability, regulatory compliance, and global climate accountability, its potential can only be realized through systemic changes, including clear regulations, financial incentives, and coordinated efforts to address adoption barriers.

This work lays a critical foundation for advancing research at the intersection of blockchain technology and sustainability, providing a framework for future studies to further explore solutions to CO_2 emissions traceability challenges and guiding policymakers, companies, and blockchain operators in leveraging blockchain for transformative environmental impact.

[8] Blockchain Integration in Food Supply Chain Emissions Management

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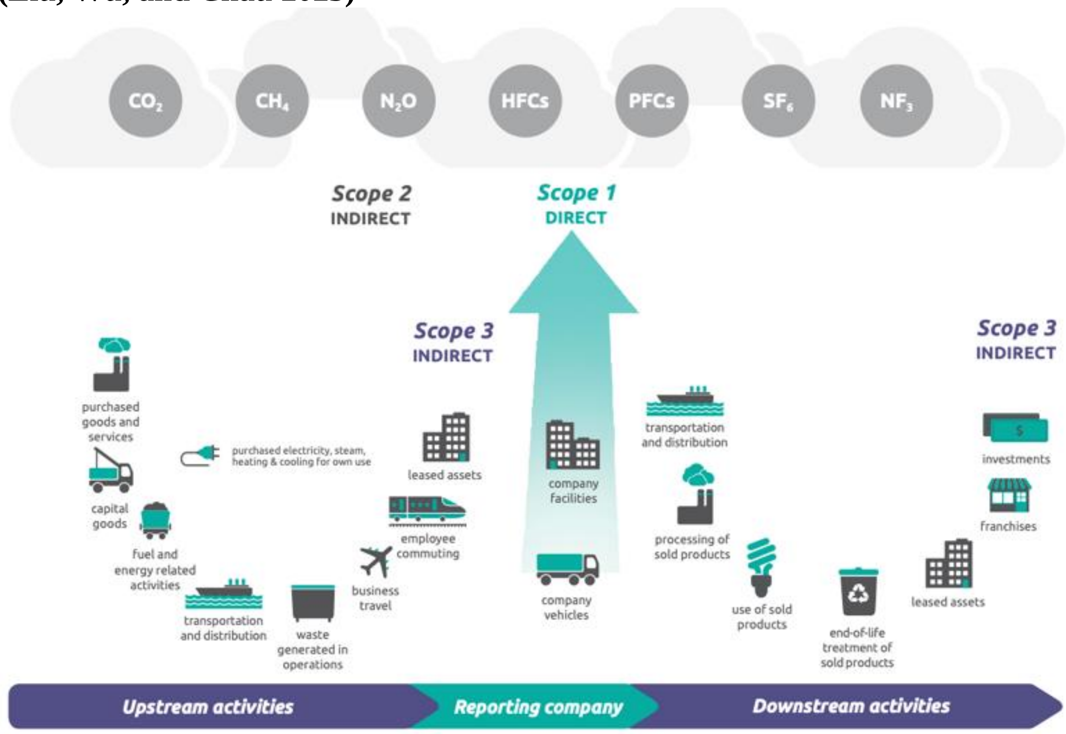
9 Appendix

Appendix 1: Overview of GHG Protocol scopes and emissions across the value chain (Liu, Wu, and Chau 2023)



Appendix 2: Interviewee Background Information

Participants	**Position**	**Industry / Specialization**	**Expertise Category**	**Geographical Location**	**Years of Experience**
Interviewee 1	Consultant	Digital innovation and Data-driven transformation. Artificial intelligence, Blockchain	Blockchain	Austria	3
Interviewee 2	Agronomist	Remote Sensing, Carbon Footprint, Regenerative Agriculture	Sustainability	Portugal	7
Interviewee 3	Senior Sales Consultant	Blockchain integration in the financial sector	Blockchain	Belgium	4

Interviewee 4	Digital Strategy Consultant	End-to-end strategies development, Blockchain	Blockchain	Germany	5
Interviewee 5	Technology Director	Blockchain implementation, Audit	Blockchain	Portugal	22
Interviewee 6	Senior Business Developer	Digital assets, Blockchain	Blockchain	USA	7
Interviewee 7	Senior Sustainability consultant	ESG, CSRD, Decarbonisation strategy	Sustainability	Germany	5
Interviewee 8	Blockchain Program Coordinator	Data Science, Blockchain	Blockchain	Portugal	10
Interviewee 9	Sustainability Analyst	GRI standards CSRD GHG Protocol	Sustainability	Portugal Min. 3	3
Interviewee 10	Technical Blockchain Product Development Manager	Blockchain, Cryprocurrency, Financial Management	Blockchain	Iran	10
Interviewee 11	Impact Coordinator and Consultant	Sustainability and Impact Assessment	Sustainability	Portugal	6
Interviewee 12	Co-Founder in the Agriculture Industry	Agriculture Regenerative Farming	Sustainability	Portugal	7
Interviewee 13	Founders Associate	Sustainability Software solutions Carbon Accounting	Sustainability	Germany	4

Interviewee 14	Sustainability Officer	Energy Management Decarbonization Strategies	Sustainability	Portugal	7

Appendix 3: Standardized Interview Questions for Blockchain Experts

1. What are the long- and short-term benefits for companies to integrate blockchain into their operations?

2. What are some successful use cases of blockchain in supply chain management that could be extended to CO_2 tracking?

3. Do you think blockchain technology has the potential to solve the current issues around inconsistent data reporting and transparency? Why or why not?

4. What specific technical, operational, behavioural challenges do you see in implementing blockchain for CO_2 emissions tracking?

5. What organizational and financial barriers exist for companies wanting to use blockchain for sustainability reporting and CO_2 emissions control?

6. How do you see blockchain evolving to meet sustainability goals, and what other areas of sustainability might benefit from blockchain integration?

Appendix 4: Standardized Interview Questions for Sustainability Experts

1. What are the primary challenges organizations encounter in tracing CO_2 emissions across their supply chains, particularly in the context of compliance with EU sustainability regulations related to CO_2 emissions?
2. Which aspects of CO_2 emissions reporting (Scopes 1, 2, or 3) present the greatest difficulties for organizations, and what specific challenges are associated with these areas?

3. To what extent do organizations experience pressure to enhance transparency regarding their CO_2 emissions, and what are the primary sources of this pressure (e.g., consumers, regulatory bodies, or investors)?

4. In your opinion, what are the primary drivers motivating organizations to increase transparency in their CO_2 emissions reporting?

5. How might forthcoming changes to EU sustainability regulations influence the adoption of emerging technologies, such as blockchain, for enhanced emissions tracking and reporting?

Appendix 5: Interview Transcript of Interview 2

CB: So, first of all, I wanted to ask you if you could briefly introduce yourself and describe your role as a Business Developer working at an agriculture business.

Interviewee 2: So, I'm XXs, and I work at XX for two years now, and I work at the research and development part of the company. Basically, I'm in charge of trials that are developed throughout the years, always towards sustainability. So, basically, exploring new strategies instead of using, for example, synthetic fertilizers, using, for example, beneficial, effective microbials, for example. o, basically, microbials that are applied in the soil with the purpose of, you know, fixing nitrogen and everything. New alternatives to conventional phytopharmaceuticals. So, basically, herbicides, whatever you can use, for example, techniques such as mulching.

I don't know if you're aware, but, for example, we use almond byproducts of our orchards. So, basically, byproducts of our orchards. The almond hull, for example, which is the exterior part of the almond, we use it, for example, to make mulch and cover the soil. For example, not applying herbicide. So, basically, the concept of circular economy is very important for us too. And, yeah, and collecting also. I'm in charge of collecting indicators that are encompassed in regenerative agriculture. For example, how much organic matter is increased with our cover crops, you know. And, for example, when it comes to carbon fixation, carbon sequestration, you know, carbon footprint, what are the exact, you know, it's very complicated to know exactly how much is being emitted or sequestrated. But, yeah, we also do that work here. And, yeah, briefly, to sum up, basically, I'm in charge for everything that involves sustainability in the production system.

CB: Thank you. In my research question for my master's thesis, I already said that I wanted to see how the blockchain can enhance the traceability and compliance of CO_2 emissions. And then, regarding sustainability tracking, what are the types of sustainability data or information that you currently report? Do you have anything in place?

Interviewee 2: So, okay, when it comes to indicators, so, as I said, one thing that is very important is to monitor how positively you are impacting your soil with your practices. So, basically, organic matter increases in the soil, this is the most common indicator that is used nowadays. And it's something that takes time to build up. And it can take up to 30 years to increase, like, 1%. So, basically, it's a very, very long process. What are the kinds, for example, when it comes to wildlife reporting, okay, when it comes to wildlife reporting, in two of our farms, we use a contract, we hire specialists, so, bird life specialists, everything to monitor the wildlife diversity, namely birds, in different ecosystems, for example, the orchard or the water dams that we have, or, for example, the riparian gallery, which is part of our farm, which is part of our ecosystem. And that's why we also work towards the requalification of water lines and everything with native species, you know. So, we also had two projects, we already had them ongoing.

And, yeah, basically, I would say that, in terms of indicators, for example, bee rights, mortality, okay? Bee mortality rights, for example, it's very important to communicate how much you are impacting the local bee hives that are basically installed in the farms. And currently, we have, our mortality rates are quite lower when comparing to, for example, with other ecosystems where they produce honey, but they are not, in fact, agricultural systems. So, basically, our mortality rate is lower when comparing to systems where they actually just produce honey, and they don't apply any agricultural products. So, basically, that's a very good indicator, right? That, basically, low impact agriculture. And what more? Coloristic composition, okay? So, basically, what kind of plants, what kind of trees we have in our farms, and what are their roles, okay, in the ecosystem? Do they attract pollinators? Do they fix nitrogen, okay? Do they repel pests? So, yeah, we also try to do that work. And lately, yeah, we finished, with another company, the carbon reporting. So, basically, I started out last year, I made the greenhouse gas emissions, okay, just in field, just in field. And this year, we work with a company that has, you know, certified methodology there and everything, and they calculated the greenhouse gas emissions at farm level, as well as the carbon that is sequestrated by those same orchards. So, basically, trees capture CO_2. We have more than 1 million trees. So, basically, it's very important to point out that role to the community, okay? And, for example, between trees, we do not have bare soil. We have natural cover crops, okay? And those same cover crops also do ecosystem service, which is not only increase organic matter content, but also capturing carbon. So, basically, these are two main ways of sequestering carbon, okay? And that's why most of the, I would say that most of the farm ecosystems that work like us are carbon negative. So, basically, they do sequester more carbon than they do emit to the atmosphere. But it's still, you know, it's still a very sensitive topic, you know? So, basically, I think people still don't believe how real is the data that basically is being displayed nowadays. And it's mainly due to the carbon credit market.

CB: Yes perfect, this would lead me to my next question what is your opinion on how well do these tools or these measures are working? In your opinion, how well do these tools that you use to measure the indicators are working? And do you think that they're accurate enough? Or is there any room for improvement?

Interviewee 2: It's still an ongoing work. I don't know if you're aware of regenerative agriculture. Okay. So, basically, it's a new trend that's arise. And people are talking a lot about it. But the indicators are still not quite decided, you know? So, basically, there's not like a framework for regenerative agriculture. So, basically, last year, we started out with our own indicators. So, basically, we do have our own templates. Okay. And it helped us a lot. And, basically, when we have conversations about, you know, about what is regenerative agriculture, having these indicators help us and help other people to clear out some questions. But the thing is, we do practice regenerative agriculture. And we are working in a sustainability report. And, basically, that sustainable report has not been concluded yet. Okay. It's yet to be finished. And it's almost finished. And only after that, perhaps, we'll know what the actual impact on the public community is.

So, when we talk about private entities, people that come to us, I think we can communicate well. They do understand well. They visit the place, and they understand what we are doing. But when we are trying to reach a broader audience, there's still a lot of, you know, a lot of lack of trust. Like people still don't know. And people, most of the people don't care. But to answer your question, yes, I think we are ready to communicate. And I think we are quite clear in what our metrics are and what our goals are. And what is the importance that the ecosystem has for us.

And, basically, I would say, yeah, room for improvement. Definitely. When it comes to biodiversity, it's actually quite complicated to evaluate what is, you know, what is a positive impact on biodiversity. Biodiversity is so many things, you know. For example, recently we started out by analysing enzymatic activity of the soil. So, basically, the microbials that work in the soil, you know, to the benefit of the plants. So, it's a very, you know, it costs a lot of money. Basically, financially, to obtain these indicators, okay, it costs a lot of money. So, basically, that's the main problem. A labour-intensive cost, in terms of cost. And then, when we talk about what is the actual benefits of communicating these results, we're still on the path of trying to figure out. But we have our own path and, basically, we'll follow it and no problem at all.

CB: Yeah, interesting. And regarding the CO_2 emissions, you said that you just started tracking them. With the help of a company. Do you also, or are you planning to track CO_2 emissions along the whole supply chain in the future?

Interviewee 2: Yes, that would be, for example, I think it's going to be mandatory in the future. It's going to be mandatory. This is mainly for compliance, and we started to work on this as early as possible. But we already had some work done for, for example, almond flour. So, since the beginning until the end of obtaining the kilogram of almond flour and then processing it to the final client. We already have like a credit to goods report on that product, okay. So, basically, I think, yeah, it's going to be part of it. Yeah, definitely. Okay.

CB: And that now you already mentioned that the biggest problem is the cost. Do you also realize any other challenges of keeping track of these indicators or in general being compliant with regulations?

Interviewee 2: Okay. In terms of cost, we have the cost and then we have the labour. So, you actually need someone to do those soil samples. For example, this year we made more than 1000 samples between our own farms. And each sample was basically done, was repeated five times. Okay. So, basically, yeah, it's a lot of work. And you were saying, can you repeat the question, please?

CB: Thank you, and do you face any other challenges regarding being compliant with EU regulations? For example, CSRD or EU taxonomy?

Interviewee 2: In any case, that's a very, very big issue and it's often associated with the topic. So of course, once with what's regulated in the DSGVO, which is of course a bit stricter for us in Europe than it is perhaps in America or the like. But the topic is actually one, as I have observed, that always comes up first. So, basically, the thing is, when we started talking about the compliance and to actually establish some goals, we had the Green Deal, right? Green Deal was actually the goal to be attained. The thing is, what they ask is completely, it's too drastic.

So, by 2030, they expect us to reduce 50% fertilizers, 50% pesticides. And basically, I think that legislation was cut, the reduction of 50% pesticides. So, basically, I would say that we are working towards it. And one of our limitations is definitely the timeline. So, basically, the EU expect us to reduce drastically our inputs. And when you talk about sustainability, we have to talk about financial sustainability. If a system is not financially sustainable, so, basically, I'm just putting in jeopardy the entire system. Yes, I can decrease by 50% our synthetic fertilizer application or pesticide application, but that will have a negative impact on the production system, meaning that the company will be weaker. Perhaps, in terms of social pillar of sustainability, perhaps some people will have to get fired in terms of balancing what is the actual credit of the companies.

So, I would say, yeah. So, labour costs increase. So, basically, people expect to see increases in the production system right away. So, basically, as I said, organic matter takes years to build up. If we want actually to, for example, let's say we have our native cover crops. So, basically, we do let them grow by their own. But there are people that actually seed. So, basically, they have to pay for the seeds. They have to pay for the equipment and the person who applied those same seeds throughout like 1,000 hectares. If you imagine that an application of those same seeds has a cost of around 200 euros per hectare, you can see how much money can be spent. How will you get that return financially speaking? Yes, you are providing a system to do a service to the ecosystem. But in terms of financial return, what will you get? It's not your cash crop, right? So, basically, I think these indicators are very taut. But people don't understand how hard it is to improve a system and how much money you actually have to spend to, for example, to obtain that same cover crop. And you have to understand one thing also. For example, those cover crops that are seeded, they are seeded when it rains in October. So, let's imagine that you seed 200 hectares, and it doesn't rain. What will happen? You basically just lost, I don't know, like 400,000 euros and nothing has grown. So, basically, these are challenges that have to be taken into account. Also, people expect agronomists to understand everything in the ecosystem. Basically, we are there to produce the best way possible. But when it comes to ecosystem services, we are not the best people to analyse what actually are those ecosystem services. How, for example, how rich is our insect community? How rich is our soil microbial community? So, basically, once again, lack of experts. I would say that's also a very big problem. So, I would say, yeah, lack of expertise.

And when it comes to carbon, I think that the biggest challenge is basically public, you know, the lack of trust that exists around that same topic. I would say that that's the same. I noticed that most of the people that I've talked about carbon footprint, they actually don't care. I think carbon footprint is actually, it's going to be mandatory. People just don't care, you know. Carbon footprint, that should be a reality for like, I don't know how many years ago. Climate change is basically real so many years ago. And right now, you know, it's just some work that should be done in the past years. So, yeah, definitely. Yeah. Labor, cost, lack of expertise, lack of trust by the audience when it comes to carbon footprint. And yeah, I think that should be those.

CB: Okay. And do you also recognize some benefits already? Because I feel like as in, because you are operating regeneratively, which is like different from other agricultural business. But as of now, do you feel some, that there are some benefits and opportunities for you as a company?

Interviewee 2: Yeah, definitely. So, everything is part of regenerative agriculture. So basically, just having information of how positively you are impacting ecosystem, which is for example, the bird life reports. That's part of regenerative agriculture, you know. Yeah, you planted the trees, you put the water there, and that had the return. That return has been measured, right? So basically, that also, the bird life report is one of the aspects that has one of the most impacts when we talk about it with people. So basically, that's a positive impact. The re-qualification of water lines. So basically, people seeing that a degraded structure is being upgraded with native species that fixate nitrogen, fixate nutrients, you know, that allow for the water lines to be permanent, to be well-structured. So, everything that is visible is always very, very, very good.

And when it comes, for example, cover crops, the cover crops that we have between rows, they are actually one of the most important parts. Not only just because they retain organic matter, it helps retain water. So basically, we can have more water in our soil. It helps us basically, when it comes to track turn, should I say, traffic, you know. So basically, when machinery can help, can basically pass through more easily because we have less compaction. At the same time, that same cover crop can help us prevent some aquifer pollution. Okay. So basically, that cover crop that is present in between rows actually absorbs the nutrients that are not absorbed by the almond crops, you know. So basically, they are not leached to the aquifer. They are leached to those same plants that will then grow. And basically, yeah. And our analysis, basically having water analysis is a very important indicator for regenerative agriculture. So do you have, you know, heavy metals in your water? Do you have ammonia in your water? You know, nitrates in your water. Nitrate is the most common indicator. And basically, our analysis indicates that we are well below what should be permitted. So basically, that's also a very good indicator. So, the impact that you are having on the aquifers, the impact that you are having in the wildlife, the impact that you're having in the soil, and the impact that you're having in the atmosphere by sequestering carbon. Another question, another thing that I also consider very important is basically our farms were installed in a degraded ecosystem. So, they had tobacco and tomato and melon for a long, long time. So, a lot of tillage, you know, tillage. So basically, machinery revolving the soil. And when we revolve the soil, basically, we kill the microbials that exist in there. We degrade organic matter. And basically, we create compaction layers. And that does not allow us to have some life, you know. And in our system, we do not till. So basically, it's permanent. So basically, it's like conservation agriculture. So basically, that helps us build up organic matter that helps us retain a higher fertility in the soil. So definitely, that's also part of regenerative agriculture.

CB: And then when it comes to companies that you're supplying the almonds for, do you feel that they are more prone to get the almonds from you? Or is it a lot of competition between all the like almond suppliers? How's the competitive landscapes? Or is that a sustainability topic there or an argument?

Interviewee 2: Okay, sure. So basically, I'm not really connected to the commercial department. The thing is that I've been noticing is this. People are consumers or whoever buys almond in bulk or whatever are making a transition or trying to make a transition from American almond, which is the biggest producer in the world, to Mediterranean almond. Why? Because of the sustainability aspects. Why? Because they use a lot of water, or they used to use a lot of water. For example, there's also an indicator. How much water do you use per hectare to produce your own almonds? So basically, in 2019, just to have an idea, in 2019, the average in California was about 12 litres to obtain one almond. And our average last year was about three to six. That has a very big impact. That transition due to water consumption, due to the way they harvest. I don't know if you're familiar with almond harvesting. For example, in America, they drop the almond to the floor. And then with some vacuums, I don't know the name, they basically just take out the almond that's in the floor and then they collect it. This causes a problem, an environmental problem, which is dust, a lot of dust that can actually be seen in satellite imagery. So that's one of the aspects that people want to make a change from California to here, because here we do not collect it on the floor. Basically, I would say that they do pay a lot of attention to what is sustainable or not. And that's why, for example, I can say I'm the one who makes the visits. And I think every person that bought almonds from XX has made a visit to our farms and was presented to our production system in order to know what we are actually doing and what they are actually buying. So that transparency is very important. So, to sum up, yes, I think the final consumer, at least this kind of final consumer, I don't know the individual one, each person has their own values. But when it comes to bulk buying, yes, sustainability is definitely something they are looking for and actual data. And we can present them. We can present that data. So yeah, definitely very important.

CB: And then coming back once more to the sustainability indicators, do you use any tools, or do you have any certificates in place that help you with this transparency?

Interviewee 2: I use any tools, and I have any certifications, as you said. Basically, the thing is we try and use as much as academic research as possible. For example, when it comes to bees, we have a student that is doing his postdoc study. And basically, he does... So basically, he's specialized in beekeeping. So, he's the one who takes care of the beehives. He's the one that evaluates the bee rate mortality. He's the one who evaluates the impact of the community's empowerment yield. Okay, so basically, you have that academic expertise. And tools, more tools. Or for... Certifications. We do, I think right now, in terms of certification, I think we are quite satisfied with the certification that we have. We have Global GAP. I don't know if you're aware of Global GAP. Well, basically, it's the most known certification in terms of agriculture. Okay. Basically, yeah. So basically, we have Global GAP. And by having Global GAP, people know that we only apply, for example, hermetic substances. We do not apply more than recommended dosage. Okay. How much water we are actually applying. And then we have add-ons. We have, for example, leaf. And we have spring, which are add-ons. And basically, those are related with water application. Sustainable water application. So those certifications help us to be more visible to the final consumer. Because we can present numbers to the final consumer. And we'll be, I don't know, what is this? You know, I don't have a term of comparison. Okay. I don't know if these guys are doing a good job or not. So basically, certifications are very important. And then we obtain FSA Gold. It's in terms of, we are the first in Europe, almond producer in Europe to obtain it. And that's like the top when it comes to sustainability practices. Okay. So basically, we were very late in obtaining it. And right now, yeah, we are looking for other certifications. We are trying to work on a regenerative agriculture certification. And a one that's more flexible. Because I don't know if you're aware of any regenerative agriculture certifications. The most known is called Regenerative Organic Alliance. But that one basically obligates you to make the transition to organic. Yeah, yeah. And when you are in organic, you cannot apply anything at all. So basically, it's not sustainable. You know, once again, in terms of financially speaking, it can compromise your entire operation. So, it's good for people that have like 20 hectares or something. But for people that actually have this kind of area, and we are aware that our practices are the best that we can actually have. So yeah, in terms of certification, we also have GRASP. GRASP is an add-on for Global Gap also. It basically is related with compromising with social obligations. So basically, the workers that we have here, all workers, even in harvest time, they have houses, they have food, they have water, they have proper conditions. And in terms of wages, you know, everything is well regulated. So that's also part of regenerative agriculture, the community pillar. How much, basically, the conditions that you basically give to your workers, the conditions that also basically you give to the community, to the local community. For example, I live in Idanha, we are establishing Idanha. Idanha is a decertified region, so there's no people around here. So, the establishment of orchards has allowed to put more people working here, has allowed more families to fixate in here. In terms of, for example, involving with local schools, you know, in terms of projects, we try to be involved as much as possible. We invite the community to come here. We, for example, receive a lot of internships of local people also to work with us and try to fixate them here as well. And in terms of the blooming stage, for example, the blooming stage, which is like the most beautiful part of the process here, every year we invite the local communities to make like a walk in the blooming orchards and then have like a lunch there, you know. So basically, these kinds of things are very, they seem small things and like ridiculous things, but things, I think there are things that matter and it's also part of regenerative.

CB: And in your last meeting that you have told me about with the IT department, where what were the indicators that you gave them that would be interesting to track for you?

Interviewee 2: The indicators that were proposed were actually quite simple. I think it was type of soil and yeah type of soil type of soil, plantation dates plantation dates, uh variety is also established water consumption, and I think they seem to talk about You know putting the bird life report on there. That's one of the biggest challenges Charlotte is What is the information that you will put in that same blockchain technology? Yeah, and how will you? You know show it because it's so much data. How can you sum up? You know so many things in just one little I don't know What would be your idea, you know, how should how should it be presented, you know? I think that's the biggest challenge Complexity of information and how to show it what is actually valuable to the final consumer, you know

CB: How are you currently recording the information do you have excel sheets or um, how do you do it?

Interviewee 2: Basically, yeah, mostly excel sheets. So manually we add the information.

CB: One last question: could you give me a feeling of Do you think you are ahead of regulations, or do you think that the pressure will increase? Throughout the next couple of years for you as a company or how's the feeling within the company?

Interviewee 2: The thing is our goal is to be Ahead, you know That's why when it comes to carbon reporting, I don't know any other company that's working towards that farm company, you know, for example in terms of Portugal I have friends that work in almond companies and it doesn't seem to exist this kind of You know, it's kind of um Value for sustainability is just to produce both, you know, yeah more almond better more money Uh, so it's a different mentality. I would say that the trials that we have are basically designed to be less reliable on synthetic Substances. So yeah, I would say that we are preparing ourselves. Yeah, I think we are we are ahead definitely. Yeah, I don't know how soon they will impose new regulations.

Appendix 6: Coding Categories and Codes

1. Benefits of Blockchain (BB)
BB1: Immutable data for CO_2 tracking
BB2: Improved traceability across supply chains
BB3: Enhanced data integrity and trustworthiness
BB4: Decentralization reducing reliance on central authorities
2. Benefits of Transparency (BT)
BT1: Increased consumer trust through accessible CO_2 data
BT2: Visibility across production stages for sustainable sourcing
BT3: Enhanced decision-making for investors and regulators
BT4: QR codes enabling product-level transparency for consumers
3. Benefits of Compliance with EU Regulations (BC)
BC1: Structured data facilitating regulatory alignment

BC2: Standardized reporting practices across supply chains
BC3: Verification of emissions data to meet EU standards
BC4: Potential competitive advantage for early adopters
4. Challenges and Barriers of Blockchain (CB)
CB1: High costs of setup and maintenance
CB2: Technical complexity and need for specialized knowledge
CB3: Integration issues within existing company systems
CB4: Limited understanding among traditional industry stakeholders
5. Challenges and Barriers of Transparency of CO_2 Emissions (CT)
CT1: Inconsistent data standards across supply chains
CT2: Limited digital infrastructure for emissions tracking
CT3: Difficulty in consolidating data across multiple suppliers
CT4: Complexity of tracking Scope 3 emissions
6. Challenges and Barriers of Compliance with EU Regulations (CC)
CC1: High costs and labor requirements for data collection
CC2: Complexity in meeting detailed reporting standards
CC3: Varying data collection standards across countries
CC4: Limited support for blockchain-based compliance in EU policy
7. Future Directions and Innovations (FD)
FD1: Integration of IoT for real-time emissions tracking
FD2: Use of oracles to bridge digital and physical data
FD3: Smart contracts for automated regulatory compliance
FD4: Adoption of energy-efficient blockchain models

Appendix 7: Comparison of Literature Review and Primary Research

Topic	Literature Review Findings	Primary Research Findings	Gaps Addressed by Primary Research	Examples from Primary Research
Transparency and Immutable Records	Highlights blockchain's ability to ensure data integrity, immutability, and transparency, enabling a trusted source of supply chain data.	Confirms benefits but stresses reliance on IoT for real-time validation. Highlights that accuracy still depends on quality of input data.	Emphasizes the critical role of IoT integration for real-time traceability, addressing a major oversight in literature.	Blockchain enabled traceability but struggled without IoT integration, e.g., monitoring crop-specific CO_2 emissions.
Scope 3 Emissions Tracking	Focuses on blockchain's theoretical ability to streamline Scope 3 tracking and reduce reliance on inconsistent or generalized data.	Reveals operational challenges, inconsistent supplier data, outdated benchmarks, and lack of standardized, automated tools for Scope 3 tracking.	Provides insights into standardizing supplier data collection and highlights the lack of scalability in current tools.	Emphasized manual data collection struggles and inconsistent emissions verification across fragmented supply chains.
Adoption Barriers	Identifies high costs, scalability issues, and the need for interoperability but neglects non-technical barriers.	Highlights cultural resistance, stakeholder scepticism (e.g., association with cryptocurrencies), and high financial entry costs.	Adds depth by addressing behavioural and cultural barriers, largely ignored in literature. Examples include trust and scepticism.	Companies delayed blockchain investments due to misconceptions about its ties to cryptocurrencies and a lack of trust.
Regulatory Challenges	Frames regulations	Exposes how unclear and	Stresses need for stable	Illustrated how inconsistent

	like CSRD and GDPR as opportunities for adoption but assumes organizations will respond proactively.	evolving regulations discourage investment and delay adoption.	frameworks and enforcement mechanisms, which are minimally discussed in literature.	enforcement allows high-emission companies to obscure data and avoid investing in advanced systems.
Broader Applications of Blockchain	Discusses blockchain in carbon credit systems and sustainability certifications but lacks practical case studies or industry insights.	Highlights practical uses like carbon credit tokenization and its role in regenerative agricultural practices.	Expands literature by demonstrating blockchain's role in real-world sustainability practices, focusing on resilience building.	Showed blockchain-enabled carbon credit trading platforms and IoT integration for regenerative agriculture tracking.

Appendix 8: Blockchain Integration in Food Supply Chain Emissions Management (Broich 2024)