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Summary of WP Student Team

Blockchain-enabled Carbon Traceability: Analyzing Its Impact on Firm Performance in the European Retail Sector

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Blockchain-enabled Carbon Traceability:

Analyzing Its Impact on Firm Performance in the European Retail Sector

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Work project carried out under the supervision of:

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Abstract

This thesis analyzes the impact of blockchain-enabled carbon traceability on firm performance in the European retail sector using a multidimensional approach. Findings reveal that blockchain-enabled carbon traceability positively impacts firm performance through improvements in supply chain performance, employee attraction and retention, and stock price performance. However, these effects rely on essential enablers. No effect on consumer purchasing behavior is observed. The study provides recommendations across five dimensions to maximize blockchain-enabled carbon traceability's potential. It contributes to research by investigating blockchain's role in carbon emissions traceability and its broader effects on firm performance, rather than focusing on isolated metrics.

Keywords: Carbon Traceability, Blockchain, Retail, Firm Performance, Transparency

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1. Introduction

In 2019, European Commission President Ursula von der Leyen announced Europe's ambition to become the world's first carbon-neutral continent by 2050. Despite the EU's efforts under the European Green Deal (EGD), progress toward this goal has been insufficient. Climate change has caused €145 billion in damages in the EU over the last decade and is expected to increase significantly in the coming years (European Commission 2022a). To combat this, greenhouse gas (GHG) emissions must be reduced considerably.

However, one industry expert interviewed for this thesis emphasizes, *"You can't improve what you can't measure"* (I7). This highlights a critical challenge: most businesses lack a basic understanding of their emission levels, particularly Scope 3 emissions (Alves, Vieira, and Partyka 2023; Yavari et al. 2023). These include all indirect emissions beyond a company's direct control - such as those from suppliers, transport, and product use or disposal – and are challenging to measure due to difficulties in obtaining data, reliance on supply chain (SC) partners, variability in data sources, and complex interdependencies (Hertwich and Wood 2018). Monitoring, reporting, and verifying (MRV) Scope 1 and 2 emissions is more straightforward. Scope 1 covers direct emissions from company-owned sources, and Scope 2 includes indirect emissions from purchased energy, such as electricity or heating (Callahan et al. 2011; Hettler and Graf-Vlachy 2024). Identifying carbon emissions across all three scopes is defined as carbon traceability (ISO 1994). It is a foundational element for addressing regulatory compliance and voluntary sustainability initiatives, enabling full environmental transparency across an organization's value chain (Lee 2012; Kaur et al. 2024).

Under the regulations set by the EGD, specifically the Corporate Sustainability Reporting Directive (CSRD), starting in 2025, companies must disclose their emissions across all three scopes (European Commission 2023a). This is particularly challenging for the retail sector, which faces significant challenges in tracing and reporting carbon emissions due to the complexity of retail SCs, diverse product portfolios, and especially the dominance of Scope 3 emissions, which account for 98% of total emissions (McKinsey 2024a). As intermediaries between producers and consumers, Europe's retailers play a crucial economic, generating €3.2 trillion in trade and contributing 20% of EU GDP in 2022 (Statista Research Department 2024a; Nolan, Zhang, and Liu 2007; Eurostat 2024). This economic significance underscores the urgency of addressing carbon traceability challenges in the retail sector, which demands innovative methods that enable comprehensive emissions reporting while ensuring financial viability and aligning sustainability strategies with accurate data on carbon footprints (Dhanda, Sarkis, and Dhavale 2022). Blockchain (BC) technology is currently gaining recognition as a tool for managing and tracing carbon footprints, especially Scope 3 emissions, and resolving issues of trust and cooperation among stakeholders (Kadry 2022). Its core features – immutability, decentralized verification, and real-time traceability – can potentially provide a framework for identifying and verifying emissions data across complex SCs (Munir et al. 2022; Huang, Weber, and Matthews 2009). F.e., the U.S. retailer Walmart piloted BC for carbon traceability with mangoes in the U.S. and pork in China, showing its effectiveness. The system increased transparency by tracing emissions data at each stage of the SC, holding suppliers accountable through carbon scorecards, and sharing environmental impact information with consumers (Tan et al. 2018; Sharma and Kumar 2021).

Despite growing interest in BC technology, current literature primarily centers on social sustainability or product origin information through BC, leaving gaps regarding carbon traceability (Liu, Wang, et al. 2023; Fraser and van der Ven 2022; Biswas et al. 2023). However, even within this scope, existing literature predominantly focuses on isolated SC performance, neglecting its broader implications for overall firm performance (Saberi et al. 2019; Cui, Gaur, and Liu 2023).

Additionally, the specific impact of Blockchain-enabled carbon traceability (BCCT) on firm performance within the European retail sector and other firm performance dimensions and synergies remain unexplored (Kamble et al. 2021; Wamba and Queiroz 2022; Carmeli, Gilat, and Waldman 2007). Therefore, this study addresses the following umbrella research question (RQ):

Umbrella RQ: How *does BCCT impact firm performance in the European retail sector?*

To address the umbrella RQ, we adopt a multidimensional approach, integrating theoretical insights from existing literature with empirical findings to explore the dimensions of BCCT - specifically from the SC, purchasing behavior, talent attraction and retention, and stock price perspective - and their impact on firm performance. This study contributes to existing research by offering a more holistic understanding of the factors influencing performance from an intrinsic firm perspective. Furthermore, it provides actionable implications for effective implementation within the European retail sector.

This thesis is structured as follows: Section 2 provides a theoretical foundation for the thesis. After presenting the methodology in Section 3, Section **Error! Reference source not found.** examines the impact of BCCT on key SC performance metrics, including efficiency, sustainability, transparency, and trust. Building on this, Section **Error! Reference source not found.** scrutinizes the impact of BCCT on consumers, focusing on its role in shaping purchasing behavior. Section **Error! Reference source not found.** then looks at internal dynamics, analyzing how BCCT adoption affects employee behavior, particularly regarding attraction and retention. Section 4 extends the analysis to the financial perspective, highlighting how BCCT affects external environmental assessment and stock price performance. Sections 5 and 6 integrate these insights and examine their cross-dimensional impact on firm performance, leading to practical implications.

The study concludes by synthesizing findings, addressing limitations, and suggesting directions for future research, providing a comprehensive and structured examination of this emerging field.

2. Background

This section sets the groundwork for analyzing BCCT's impact on firm performance. Section 2.1 outlines the regulatory framework, Section 2.2 examines the current state of the art in carbon traceability, Section 2.3 explores carbon traceability in the retail sector, and Section 2.4 explains BC technology.

2.1. Regulatory Framework

As part of the EGD, the CSRD mandates Environmental, Social, and Governance (ESG) reporting for EU and non-EU firms with considerable operations in the EU. Social disclosures emphasize human rights, diversity, and labor practices, while governance requirements target corporate ethics, anti-corruption measures, and the integration of sustainability into strategic decision-making. This study focuses on the Environmental Pillar of the ESG, which addresses climate-related risks, GHG emissions, and resource consumption (LSEG 2024). According to the CSRD, organizations must trace and report their Scope 1, 2, and 3 emissions quarterly, completing over 200 mandatory fields on an EU portal. For the fiscal year 2024, large public-interest entities with over 500 employees must comply with stricter regulations. For the fiscal year 2025**,** the mandate expands to include large companies reaching at least two criteria: more than 250 employees, a net turnover exceeding €40 million, or total assets over €20 million. Listed small and medium-sized enterprises must comply with the reporting requirements starting in fiscal year 2026, but they can delay compliance until 2028 (European Commission 2023a). Non-EU firms must disclose emissions to access the EU market, promoting comprehensive carbon emission data (Perdana and Vielle 2022).

In practice, the stricter regulations pose significant challenges for many companies across Europe, particularly in independently determining the carbon emissions generated by their overseas suppliers. The EU Commission advises businesses to request carbon emission data directly from them. However, this process can be costly and complicated, especially in multi-tiered SCs where data reliability may be difficult to ensure (BDI and DIHK 2024). Therefore, many companies remain unprepared to meet regulatory requirements, which can result in financial penalties and exclusion from the market (De Villiers, La Torre, and Molinari 2022; Lütkehaus et al. 2022).

2.2. Current State of the Art in Carbon Traceability

Implementing a robust carbon traceability system may offer significant advantages for companies navigating the European regulatory landscape. Firms must ensure near real-time, verifiable, and detailed tracing of individual product emissions while safeguarding business confidentiality and proprietary information (Harbich et al. 2021; Heiss et al. 2024). MRV systems are a common tool for this. In the monitoring phase, companies collect activity data, quantifying business operations that generate GHG emissions. These activities are then translated into emission estimates using emission factors, which are standardized, projected coefficients, often derived from databases like those provided by the Intergovernmental Panel on Climate Change (Heiss et al. 2024). Life Cycle Assessment (LCA) is often used in this context. LCA is a systematic method for evaluating the environmental impacts of products, processes, or services across their entire lifecycle, from raw material extraction to disposal (ISO 1997). In the reporting phase, the calculated emissions are compiled into a report, which must adhere to key accounting principles: relevance, accuracy, completeness, consistency, and transparency. These principles aim to enhance the reliability of the data but cannot entirely mitigate the limitations of approximation (WRI and WBCSD 2011).

Finally, verification involves a third-party review to confirm the report’s compliance with guidelines and regulatory standards (Heiss et al. 2024).

Conventional MRV systems are limited by long, annual reporting cycles and centralized structures that reduce transparency and trustworthiness (European Commission 2023a; European Commission 2023b). Furthermore, the systems often lack sufficient digitization and automation, resulting in higher costs, increased errors, and inefficiencies (World Bank 2022).

2.3. Carbon Traceability in the Retail Industry

As mentioned before, this thesis focuses on the retail industry, which includes all activities involved in providing goods or services directly to end consumers for personal and non-business objectives. These activities can occur in physical stores, online platforms, or other formats. Given the large share of indirect emissions in retail paired with its vast reach and impact, the sector holds considerable potential to drive large-scale environmental improvements by employing cutting-edge carbon tracing methods (McKinsey 2024a; Ferreira et al. 2019).

However, retail SCs differ from other industries in several ways, making carbon emission traceability more challenging. Retail SCs are inherently more complex than other industries due to the larger and more diverse network of suppliers that retailers must manage (Ge et al. 2019). This diversity arises from a wide product range sourced from various regions and production stages, in contrast to manufacturers who often operate within more streamlined and vertically integrated SCs. Additionally, retail SCs tend to be highly dynamic, as retailers frequently adjust their supplier base to respond to shifts in consumer demand, cost pressures, or seasonal variations. This dynamic nature further complicates establishing and maintaining consistent carbon traceability systems across the SC (Serdarasan 2013). Fragmented data-sharing systems exacerbate these challenges, as multi-level SC stakeholders use inconsistent standards, resulting in incomplete data. Process standardization, regional differences, language barriers, and infrastructure accessibility further complicate carbon traceability in the retail sector (Cura, Jain, and Niinimäki 2022; Stenzel and Waichman 2023).

2.4. Blockchain

In recent years, BC has gained significant attention for being an effective tool for tracing information along value chains and addressing the retail challenges mentioned above (Dong et al. 2023). BC can add significant value to businesses by providing secure transaction verification, reducing costs by eliminating intermediaries and improving efficiency by minimizing delays (Nowiński and Kozma 2017). The growing importance of BC is reflected in its rapid rise in economic significance. While investment in BC reached $800 million in 2014-2015, its projected business value is expected to grow to $3.1 trillion by 2030 - comparable to the current GDP of the entire African continent (McKinsey 2016; Gartner 2022; Statista 2024).

2.4.1. Blockchain Definition and Evolution

According to Tabatabaei, Vitenberg, and Veeraragavan (2023, p.3), the "term of 'Blockchain' generally refers to a paradigm for maintaining information in a distributed system that is characterized by a number of properties." The basic idea behind BC dates back to the 1980s when David Chaum introduced the blind signature. This cryptographic method that enabled anonymous payments by preventing third parties from identifying details such as the payee, amount, or timing of the transaction (Chaum 1983). BC first gained widespread attention in 2008 with the creation of Bitcoin, the first cryptocurrency to showcase BC as a decentralized system (Nakamoto, 2008). Nowadays, BC's practical application extends beyond Bitcoin (Nagar and Manoharan 2022). Specifically, Gurtu and Johny (2019) highlight that BC transitioned from its original use of secure money transactions into becoming a key element in a growing network of new technologies such as artificial intelligence (AI) and Internet of Things (IoT).

2.4.2. Blockchain Characteristics

BC is characterized by its immutability, meaning that it cannot be changed once data is recorded. It operates on a decentralized model that removes the reliance on third-party intermediaries like banks. Transparency is ensured since transactions are securely recorded on a peer-to-peer network, which typically maintains an accessible and transparent ledger. Consensus and advanced encryption algorithms guarantee that data remains consistent and protected across the network (Capocasale, Gotta, and Perboli 2023; Tripathi, Ahad, and Casalino 2023). For this reason, BC is often referred to as distributed ledger technology (Hilary 2022). Furthermore, it enables rapid validation and permanent transaction recording, improving security and traceability. Users maintain pseudonymity through randomly generated addresses, while each transaction is linked to an unused previous one, enabling effective fraud detection and tracking through time-stamped, verifiable records (Capocasale, Gotta, and Perboli 2023; Tripathi, Ahad, and Casalino 2023).

2.4.3. Blockchain Workflow

BCs consist of sequentially linked data blocks. When a user initiates a transaction, it is sent to the network for validation, ensuring system integrity and security (Vaigandla et al. 2023). Once validated, the transaction is added to a new block, which is cryptographically linked to the previous block, forming an immutable chain. The first block, the genesis block, does not reference a predecessor (Tripathi, Ahad, and Casalino 2023; Vaigandla et al. 2023). Transactions are secured through digital signatures, with users generating signatures using their private keys, while public keys serve as verifiable addresses for verification. These mechanisms ensure the authenticity and immutability of transactions, strengthening BC security (Rajasekaran, Azees, and Al-Turjman 2022). Each block within a BC contains a header, which includes essential metadata like timestamps and cryptographic hashes linking it to previous blocks and a body that records verified transactions. These components together ensure transparency, security, and resistance to tampering (Dong et al. 2023).

2.4.4. Consensus Mechanism

Decisions in BCs are made through consensus mechanisms, which describe a process by which nodes in a BC network collectively verify transactions and determine the order in which they are recorded on the BC (Nagar and Manoharan 2022).

Proof-of-Work (PoW). In BC networks like Bitcoin, the PoW consensus mechanism relies on miners to perform complex computational puzzles to validate transactions and create new blocks, securing the network through energy-intensive competition (Nagar and Manoharan 2022).

Proof-of-Stake (PoS). PoS represents an alternative BC validation approach, where network participants secure the right to verify transactions by depositing and temporarily locking their cryptocurrency. Validator selection is weighted by the size of their financial stake, encouraging network participants to maintain a significant, committed investment in the BC ecosystem. It is substantially less energy-intensive than PoW (Nguyen et al. 2019).

2.4.5. Types of Blockchain

Namasudra and Akkaya (2023) state that there are three types of BCs, namely public or permissionless, private or permission, and consortium. Vaigandla et al.'s (2023) research highlight hybrid BC as a fourth major type.

Public or permissionless BCs. Public or permissionless BCs, like Bitcoin, are decentralized, allowing participants to join freely without approval. They prioritize transparency and security but often face slower transaction speeds due to extensive verification processes (Vaigandla et al. 2023).

Private BCs. Private BCs, in contrast, operate within closed, centrally controlled networks where participants and rules are pre-approved. These BCs offer faster transactions and scalability but sacrifice decentralization and security (Dong et al. 2023; Vaigandla et al. 2023; Namasudra and Akkaya 2023).

Hybrid BCs. Hybrid BCs merge features of public and private BCs, offering controlled data visibility while ensuring transaction transparency through Smart Contracts. They provide flexibility, balancing privacy with transparency (Vaigandla et al. 2023).

Consortium BCs. Lastly, Consortium BCs enable multiple stakeholders to interact within a semi-centralized network, thereby maintaining participant privacy while facilitating efficient, transparent value chain interactions. Their unique architecture allows for accelerated transaction processing and collaborative monitoring, making them well-suited for complex, multi-stakeholder industries requiring robust, privacy-preserving data exchange (Vaigandla et al. 2023; Namasudra and Akkaya 2023). This structure represents a potential approach for retailers and carbon traceability, offering a strategic balance between decentralization and controlled collaboration.

2.4.6. Smart Contracts

Smart Contracts can be a transformative tool within specific BC ecosystems. They are self-executing programs that automatically enforce agreements when pre-defined conditions are met. Unlike traditional paper contracts that require notarization, Smart Contracts operate autonomously through code, eliminating the need for intermediaries to monitor transactions. The contract is executed only when all parties meet the specified requirements, making transactions faster, safer, and more cost-effective while ensuring accuracy and trustworthiness. However, these automated contracts are conspicuously absent from platforms like Bitcoin, demonstrating that their functionality is application-dependent (Bao et al. 2021; Nagar and Manoharan 2022).

2.4.7. Other Technologies

Notably, other technologies have been extensively researched in the context of BCCT.

IoT. IoT is a network of physical devices equipped with sensors, communication technologies, and processing units that can interact with each other and online services. These interconnected "smart" devices enable real-time data exchange and remote monitoring in applications ranging from home automation to industrial systems and monitoring carbon emissions within SCs. IoT devices typically integrate sensors to collect data, communication transceivers to transmit information, and microcontrollers to process and manage interactions in real-time, enabling sophisticated, automated functionality across multiple industries (Fraga-Lamas et al. 2016; Lee and Chung 2011).

AI. AI adds intelligence to machines, enabling them to gather information, process complex data sets, and make autonomous decisions. While AI systems often require training, they can analyze and interpret data, such as carbon emissions, independently. When connected to IoT, AI processes data collected by IoT nodes and transfers it to cloud platforms for advanced analysis. The system then generates insights, makes decisions, and communicates processed results to specific users or devices within the network, creating a sophisticated, adaptive technology ecosystem (Fraga-Lamas, Lopes, and Fernández-Caramés 2021; Schuetz and Venkatesh 2020).

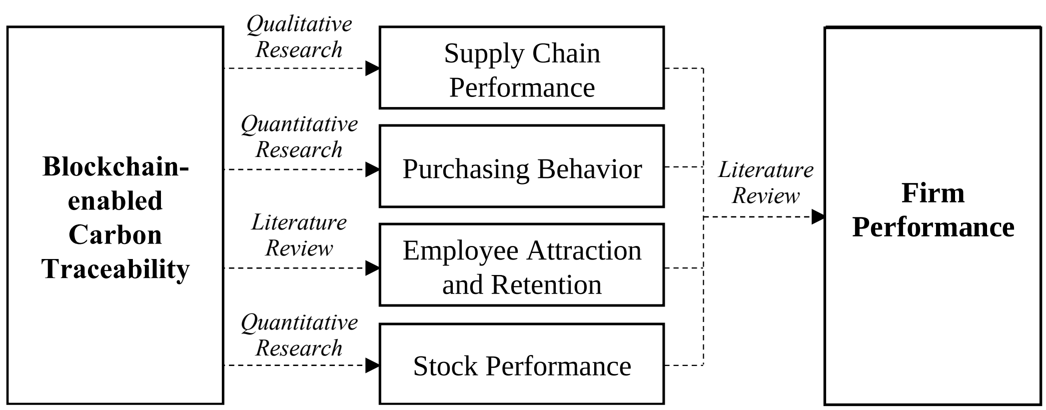
However, while both technologies offer the potential to complement emissions tracing, this study concentrates specifically on BC.

To summarize, BC's core characteristics could be translated into an effective tool for tracing carbon emissions if the necessary information is uploaded by every player along the SC. Ultimately, this could support the development of a green SC by providing transparency from production to final consumption (Zhao et al. 2022; Wang, Wang, and Abareshi 2020). Notably, the technical implementation is not within the scope of this thesis.

3. Methodology Overview for Individual Parts

To examine the impact of BCCT on retail performance in Europe, we analyze four key dimensions: SC performance, purchasing behavior, employee attraction and retention, and stock price performance. Finally, we evaluate how these dimensions individually and collectively impact firm performance using a mixed method (Figure 3), analyzing their relative impacts and potential synergistic relationships utilizing literature.

Figure 1. *Theoretical Framework.*



(Other sections of the thesis were originally included here, but had to be removed to comply with submission requirements.)

4. Stock Price Performance

According to Morgan Stanley (2024), the growing relevance of sustainability for investors is evident, as over half of individual investors plan to increase their allocations to sustainable investments next year, with climate action as the primary focus. However, 63% of respondents cite a lack of transparency and trust in reported ESG data and concerns over greenwashing, underscoring the need for robust solutions like BCCT to enhance credibility.

The objective of this part of the thesis is to investigate the impact of BCCT on the stock price performance of European retailers. As discussed in the previous sections, BCCT systems have emerged as a promising technological tool to provide immutable and transparent records of carbon footprints across SCs. However, despite their potential, BCCT adoption remains limited in the retail sector, resulting in significant gaps in understanding its broader financial impacts (Naranjo Tuesta, Crespo Soler, and Ripoll Feliu 2020).

This section examines BCCT as an independent variable and its impact on stock price performance, the dependent variable. The Environmental Pillar Score (EPS), a metric that evaluates a company's environmental performance, serves as a mediating variable.

Despite growing interest in BC technology for sustainability purposes, no prior research has specifically analyzed the impact of BCCT on the EPS (Liu et al. 2024). Existing literature often focuses on broader ESG frameworks or the operational benefits of BC but lacks targeted evaluations of its impact on specific environmental performance metrics (Simin Chen, Song, and Gao 2023). The role of this score as a mediator between operational sustainability improvements and financial performance also remains underexplored. This is particularly notable in light of the extensive body of literature examining the relationship between ESG performance and financial outcomes. Over 2,000 academic studies have explored this relationship, with approximately 70% identifying a positive correlation between ESG scores and financial returns (McKinsey 2020). However, these studies often treat ESG as a unified construct without isolating the specific contributions of individual components like the EPS (Nazir et al. 2024). By focusing exclusively on the EPS, this section offers a nuanced analysis of how implementing BCCT impacts retailers' environmental performance ratings and, in turn, impacts their stock price performance. To this end, this section aims to answer the following RQ using a quantitative approach:

RQ_4: *Does BCCT impact stock price performance of European retailers?*

This addresses a critical gap in the literature, as most existing research tends to generalize across the broader ESG spectrum, overlooking the distinct mechanisms through which environmental improvements can drive financial outcomes. Furthermore, these dynamics are explored within the unique context of the European retail market, where stringent environmental regulations and evolving consumer expectations play a pivotal role (Arvidsson and Dumay 2022).

4.1. Theory and Hypotheses Development

This section synthesizes findings from existing literature to develop the hypotheses that guide the empirical analysis of RQ_4. Due to the increasing demand from investors and regulators for standardized sustainability metrics, ESG reporting has significantly evolved over the past decades (Chand and Kour 2024). Early ESG practices were fragmented, relying on self-selected indicators, leading to inconsistencies across industries and regions (Vorontsova, Agafonova, and Bilan 2023). Furthermore, such frameworks often lacked the granularity required to assess specific dimensions, particularly environmental performance (Alsayegh, Abdul Rahman, and Homayoun 2020). Advanced methodologies, such as the LSEG Data & Analytics[1] ESG framework used in this paper, now provide more precise, industry-specific assessments aligned with modern corporate disclosure practices.

Precisely, the EPS consists of 298 criteria grouped into three subcategories: emissions, resource use, and innovation (Table 10). These categories provide a detailed assessment of a company's environmental performance. F.e., the emissions category evaluates carbon-related metrics like total emissions (Scope 1, 2, and 3), but also reductions, and trading mechanisms. The resource use category assesses water and energy usage, efficiency policies, and sustainable procurement

[1] Formerly Refinitiv, which is an American-British global provider of financial market data and infrastructure.

practices. Finally, the innovation category tracks green product initiatives, environmental R&D, and lifecycle analysis of products (Refinitiv Workspace 2024). Carbon traceability enables firms to monitor, report, and verify carbon emissions across complex value chains, thereby enhancing environmental performance. Empirical studies demonstrate that robust carbon traceability mechanisms can reduce emissions, improve data accuracy, and ensure regulatory compliance (Ju et al. 2022; X. Cui et al. 2022). For retailers, implementing traceability systems directly impacts environmental metrics by providing actionable insights into high-emission areas (Marconi et al. 2017). BCCT further enhances this process by increasing transparency, reducing data fragmentation, and standardizing reporting, which ultimately can lead to improved EPS (Kadry 2022). This aligns with Section **Error! Reference source not found.**, which finds that assuming the necessary enablers are implemented, BCCT positively impacts sustainability performance as reflected in the EPS.

Grounded in these findings, the following hypothesis is proposed:

Hypothesis 4 (H_4). *BCCT positively affects the EPS of European Retailers.*

A growing body of research links strong environmental performance to improved financial outcomes, particularly regarding stock price performance (Alexopoulos, Kounetas, and Tzelepis 2018; Delmas, Nairn-Birch, and Lim 2015). Freeman and Phillips' (2002) Stakeholder Theory suggests that firms addressing environmental concerns foster stronger relationships with stakeholders, including suppliers, customers, investors, and regulators, leading to financial benefits. Similarly, Legitimacy Theory posits that companies demonstrating compliance with societal norms and environmental standards improve their legitimacy, which can positively impact stock price performance (Bansal and Clelland 2004). An improved EPS signals a retailer's commitment to sustainability, which resonates strongly with investors prioritizing environmental risk management and long-term value creation (Yu and Zhao 2015). For European retailers operating under intense scrutiny regarding their environmental impact, higher EPS enhance their appeal to institutional investors and sustainability-focused funds (Durán-Santomil et al. 2019). Firms with higher EPS values often demonstrate proactive environmental strategies that positively influence market perceptions, stakeholder trust, and long-term financial performance (Zhou, Liu, and Luo 2022). As a result, retailers with strong environmental performance are likely to experience enhanced stock price performance (Yadav, Han, and Rho 2016).

Additionally, empirical research highlights the potential of the EPS to mediate the relationship between sustainability initiatives and financial performance by signaling reduced environmental risks and enhanced operational efficiencies to investors (Abdi, Li, and Càmara-Turull 2020). BCCT can improve environmental metrics through transparent and accurate tracing of emissions, potentially leading to investors valuing this as a credible indicator of a company's sustainability performance (Basu, Deb, and Singh 2023). This suggests that the EPS, which most companies publish annually, can serve as a signal for sustainability to investors. This aligns with the Signaling Theory, stating externally visible attributes can shape decisions of external stakeholders, explained in more detailed Section **Error! Reference source not found.** (Turban and Greening 1997). Consequently, EPS can act as a critical mediator linking BCCT to stock price performance, as visualized in Figure 11. This mediating role is grounded in the Resource-Based View (RBV), which posits that a firm's sustained competitive advantage stems from resources that are valuable, rare, inimitable, and non-substitutable (Barney 1991). An enhanced EPS can therefore be conceptualized as an intangible asset contributing to a firm's competitive positioning. Thus, the following hypothesis is proposed:

Hypothesis 5 (H_5): *An increased EPS positively affects the stock price performance of European retailers.*

4.2. Exploration of BCCT's Impact on the Environmental Pillar

To test H_4, we quantify the impact of BCCT on EPS. This section develops a structured framework to classify criteria based on the degree to which BCCT impacts them. Using this framework, the EPS criteria are categorized into three dimensions: (1) directly affected by BCCT, (2) indirectly affected by BCCT, and (3) not affected by BCCT.

4.2.1. EPS Criteria Classification Framework

The framework draws from existing literature on sustainability metrics, SC transparency, and carbon traceability systems to establish a theoretical foundation. The following subsections provide an overview of the EPS methodology and justify the classification of criteria with supporting evidence from relevant studies.

The first category of EPS criteria includes those *directly affected by BCCT*, encompassing metrics where implementing BCCT leads to measurable improvements. For instance, BCCT directly affects criteria like "CO_2 Estimation Method" by enhancing emissions reporting accuracy by ensuring tamper-proof and transparent records, thereby reducing data inaccuracies and the potential for fraud, as presentet in detail in Section **Error! Reference source not found.**. Studies such as those by Franke, Schletz, and Salomo (2020) demonstrate that BC-based systems can significantly improve the reliability of emissions data. Similarly, BCCT facilitates precise tracing of carbon emissions across various stages of the SC, a capability that directly supports SC carbon footprint visibility. Zhang et al. (2020) emphasize the role of BC in providing granular insights into high-emission areas, enabling firms to implement targeted interventions.

The second category comprises EPS criteria *indirectly affected by BCCT*, where adopting BCCT results in secondary effects. F.e., BCCT enhances policy adherence and regulatory compliance by offering verifiable and standardized data to meet carbon-related policy requirements (Section **Error! Reference source not found.**). This is particularly salient in the context of stringent EU regulations, as highlighted by Manupati et al. (2020). Additionally, BCCT fosters supplier engagement in sustainability by increasing transparency within the SC, motivating suppliers to align with sustainability goals to remain competitive. Sassen, Hinze, and Hardeck (2016) provide evidence of how such transparency can enhance supplier collaboration on environmental objectives. Moreover, BCCT supports renewable energy usage metrics by fostering transparency in energy procurement processes, thereby incentivizing shifts toward sustainable energy sources.

The final category includes EPS criteria *not affected by BCCT*, which pertain to metrics beyond the impact of BCCT. For instance, biodiversity conservation metrics, which focus on species protection and habitat restoration, typically require separate monitoring systems and are not important for retailers' carbon traceability. Similarly, non-carbon environmental indicators such as water usage lie outside the capabilities of BCCT systems, as noted by Balasubramanian et al. (2024).

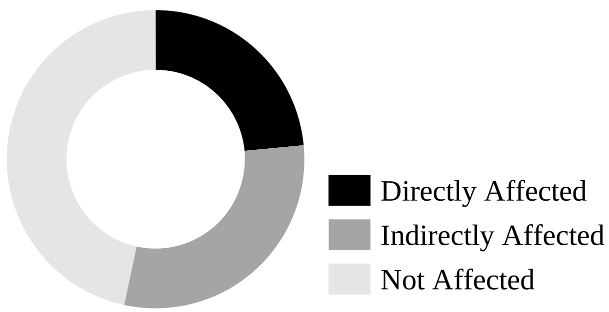
Based on the outlined framework, we categorize the EPS criteria into three dimensions (see *EPS Criteria Classification* Excel file for detailed rationale). This categorization provides a clear view of BCCT's impact on environmental metrics, highlighting its strengths and limitations. These classifications form the basis for the subsequent empirical analysis, linking BCCT-driven improvements to overall EPS performance.

4.2.2. Results

The results demonstrate the impact of BCCT on the EPS - out of all EPS criteria, 70 (23.5%) are directly affected by BCCT, 89 (29.9%) are indirectly affected, and 139 (46.6%) are not affected (Table 11). Overall, BCCT influences 12.9% of the total ESG, with 2.5% of criteria directly impacted and 10.4% indirectly.

In the resource use subcategory, which accounts for 3.7% of the EPS, 7 out of 57 criteria (12.3%) are directly impacted, 32 (56.1%) are indirectly affected, and 18 (31.6%) are unaffected. The emissions subcategory, representing 5.5% of the EPS, shows the strongest direct impact, with 62 out of 196 criteria (31.6%) directly influenced, 33 (16.8%) indirectly affected, and 101 (51.5%) not impacted. For the innovation subcategory, which constitutes 13.8% of the EPS, only 1 of the 45 criteria (2.2%) is directly affected, 24 (53.3%) are indirectly influenced, and 20 (44.4%) remain unaffected.

Figure 2. *EPS Criteria Classification Results.*



The results indicate confirmation of H_4: BCCT can positively affect the EPS as it influences 53.4% of all EPS criteria. These results align with the RBV, showcasing BCCT as an intangible asset enhancing sustainability metrics and Signaling Theory, where improved EPS signals reduced risks and operational efficiency.

4.3. Exploration of the EPS Impact on the Stock Price Performance

After analyzing the impact of BCCT on the EPS, we now examine how the environmental performance of European retailers affects financial outcomes, specifically exploring the impact of EPS on stock price performance.

4.3.1. Research Design

To quantify the impact of the EPS on stock prices, this study analyzes a sample of 622 publicly listed European retailers using annual stock returns and environmental indices over 15 years.

4.3.2. Data Source

The data is sourced from LSEG Data & Analytics, one of the world's leading ESG data platforms. LSEG provides ESG scores to evaluate companies' sustainability performance, focusing on the Environmental Pillar. The EPS is derived from over 800 auditable measures, distilled into industry-specific key metrics to ensure relevance and comparability (LSEG 2024).

4.3.3. Sample Selection

To examine the relationship between EPS and stock price performance, we construct a consistent sample using ESG ratings available over the longest feasible time period. A primary challenge is the limited availability of ESG data, both in cross-sectional and time-series dimensions - an issue common in ESG research (Lioui and Tarelli 2022). Accordingly, a 15-year period is selected to ensure sufficient data quality and reliability.

The analysis uses annual data points and focuses on publicly listed European retail firms, which include the largest firms by market capitalization, offering a comprehensive and consistent selection of key players in the European retail sector. The sample covers firms across diverse retail categories, including general merchandise, apparel, luxury goods, and supporting industries such as logistics and e-commerce. This approach enables a comprehensive assessment across the retail value chain. Notably, the sample also includes firms that lost market capitalization over the past 15 years to mitigate survivor bias (Carpenter and Lynch 1999).

4.3.4. Dependent Variable: Closing Stock Price

The dependent variable is the annual closing stock price, defined as the stock's price at the close of trading on the last trading day of the calendar year. If no trades occur on that day, the most recent prior trading day's price is used, provided it falls within 378 calendar days (54 weeks) (LSEG 2024). Annual closing stock prices are widely used in financial research as they offer a clear and comparable measure of firm valuation over time (Brennan 1995). This metric is particularly relevant for this study, as it could capture the financial impact of BCCT adoption on European retailers. Furthermore, using annual data aligns with the reporting cycles of ESG metrics, facilitating the integration of EPS as a mediating variable.

This approach is consistent with prior studies on stock price performance and ESG impact, ensuring comparability and robustness in the analysis (La Torre et al. 2020; Luo et al. 2024).

4.3.5. Independent Variable: Environmental Pillar Score

The EPS serves as the independent variable, measuring a company's environmental performance and ability to manage environmental risks and opportunities (Sahin et al. 2022). The EPS serves as the independent variable, measuring a company's environmental performance and its ability to manage environmental risks and opportunities (Sahin et al. 2022). The EPS is calculated using a percentile rank methodology, benchmarking companies against industry peers. This approach normalizes quantitative data, such as carbon emissions, and scores Boolean metrics, such as the presence (1) or absence (0) of water efficiency policies. The final EPS, dynamically weighted using the LSEG Magnitude Matrix, is presented on a 0 – 100 scale, where higher scores reflect superior environmental performance. Regular updates ensure the EPS reflects current corporate disclosure (LSEG 2024).

To isolate the environmental impact, this study excludes the Social and Governance Pillar Score of the ESG. This pillar-specific approach aligns with established ESG research practices, allowing for a detailed investigation into the role of environmental transparency and accountability -

enhanced by BCCT - in improving firm valuation and market performance (Gonçalves, Louro, and Barros 2023).

4.3.6. Control Variables

To isolate the effect of the independent variable of interest and account for potential confounding factors, we include control variables. Following established practices in ESG and financial performance research, this study incorporates seven control variables to account for additional factors (Luo et al. 2024; Korinth and Lueg 2022; La Torre et al. 2020; Sassen, Hinze, and Hardeck 2016). All control variable data are sourced from the LSEG database. These variables include the Social Pillar Score (SPS) and Governance Pillar Score (GPS), capturing aspects of a firm's social and governance performance. Firm size ($SIZE$) is measured as the total number employees. We use return on assets (ROA) to measure a firm’s profitability, calculated by the net income divided by total assets. The current ratio ($CURA$) is calculated as the current total assets divided by the current total liabilities, assessing short-term liquidity. Furthermore, we include a company’s revenue (REV) and retained earnings ($RET\ EARN$) as possible influencing factors on financial stability and growth potential, measured as total revenue from sales and services and cumulative net earnings reinvested into the company, respectively.

4.3.7. Methodology

First, we cleaned the dataset by removing outliers, addressing missing values, and ensuring consistency to improve the accuracy and reliability of the analysis. This study employs a linear regression model to investigate the relationship between stock price performance and a set of explanatory variables.

The regression equation is specified as follows:

$$Y = \beta_0 + \beta_1 EPS + \beta_2 SPS + \beta_3 GPS + \beta_4 SIZE + \beta_5 REV + \beta_6 ROA + \beta_7 RET\ EARN + \beta_8 CURA + \varepsilon$$

Where Y represents the annual stock price, β_0 the intercept, and ϵ the error term.

To ensure robustness, the models undergo a series of diagnostic tests. VIF are calculated to assess multicollinearity, revealing no significant correlation among independent variables. Residual plots confirm the assumption of homoscedasticity, supporting the reliability of the regression results. Autocorrelation is examined using the Durbin–Watson test, which confirms the independence of residuals. Sensitivity analysis further validates the results by excluding certain control variables and testing alternative model specifications, confirming the stability of the findings across different setups.

4.4. Results

This section presents the study's findings, including descriptive statistics, regression results, and additional analyses.

4.4.1. Descriptive Statistics

Table 13 summarizes the descriptive statistical results. The mean EPS is 58.678, with a standard deviation of 24.287, indicating moderate variability in environmental performance across firms. The EPS ranges from 0.760 to 98.470, reflecting a broad spread in environmental practices. The SPS and GPS have means of 63.158 and 50.920, respectively, with standard deviations of 23.110 and 22.454. These results suggest slightly lower variability in governance scores compared to social scores, both of which are lower than the variability of EPS.

Skewness and kurtosis measures provide further insights into the distributions. The EPS exhibits slight negative skewness (−0.317), suggesting a small number of firms with exceptionally high scores and a kurtosis value of −0.745, indicating a flatter-than-normal distribution. Similarly, the SPS and GPS show slight negative skewness (−0.614 and −0.138, respectively) and flattened distributions, with kurtosis values of −0.381 and −0.896.

4.4.2. Regressions Results

This section presents the regression analysis examining the relationship between EPS and stock price, corresponding to H_5. The analysis incorporates relevant control variables to account for other factors that may impact stock price performance.

The model explains 27.9% of the variance in closing stock price ($R^2 = 0.279$), with an adjusted R^2 of 0.248, accounting for degrees of freedom and model complexity. As shown in Table 12, the overall model is statistically significant (F-statistic = 9.079, $p < 0.001$).

Table 14 presents the regression standardized coefficients, standard errors, and p-values. The EPS ($\beta = 1.770$, $p = 0.017$) is a significant positive predictor of the closing stock price, supporting H_5. Specifically, a one-unit increase in EPS corresponds to a 1.77-unit increase in stock price, holding other variables constant.

In contrast, the GPS has a significant negative effect on the closing stock price ($\beta = -1.993$, $p = 0.002$). The SPS shows a positive but statistically insignificant relationship ($\beta = 0.945$, $p = 0.181$), suggesting its effect on stock price performance may be limited or context-dependent.

Among the control variables, the current ratio has the most substantial and significant impact ($\beta = 123.592$, $p < 0.001$).

Revenue also shows a positive and significant relationship ($\beta = 2.065\times10^{-9}$, $p = 0.037$), indicating that higher revenue contributes to better stock price performance. However, firm size ($\beta = 3.853\times10^{-4}$, $p = 0.557$), return on assets ($\beta = -7.758\times10^{-9}$, $p = 0.780$), and earnings ($\beta = -5.159\times10^{-9}$, $p = 0.090$) are not statistically significant.

Overall, the regression analysis supports H_5: the EPS emerges as a significant positive predictor of stock price performance. This finding underscores the critical role of environmental practices in enhancing the market valuation of European retailers.

4.5. Discussion

Moreover, this study extends the literature on ESG metrics by specifically addressing the European retail sector, which faces unique regulatory and stakeholder-driven challenges. Regulatory pressures, such as the EGD and CSRD, demand heightened transparency and comprehensive emissions reporting.

This study demonstrates that BCCT can enhance the stock price performance of European retailers. The findings confirm H_4, showing that BCCT could influence the majority of EPS criteria. This result highlights BCCT's role as a transformative tool in enhancing sustainability metrics. This capability aligns with prior research emphasizing BC's ability to reduce carbon emissions, enhance compliance, and improve the accuracy and trustworthiness of sustainability reporting for investors (Franke, Schletz, and Salomo 2020; Kadry 2022). BCCT ensures consistent, tamper-proof reporting of emissions data, addressing information asymmetry and providing a more accurate foundation for determining the EPS and, in turn, transparently signaling the environmental performance to investors.

Additionally, the results support H_5, which could reveal that higher EPS values positively correlate with stock price performance. These findings underscore the mediating role of EPS in linking BCCT adoption to improved financial outcomes. The positive association between EPS and stock price performance reinforces existing evidence on the financial value of robust sustainability practices. This relationship is particularly pertinent for retail firms facing heightened scrutiny over their environmental impact (Durán-Santomil et al. 2019). For European retailers operating under intense scrutiny, strong EPS signals a clear commitment to sustainability, which especially resonates with sustainability-conscious investors. Due to the rise of these investors, the EPS is expected to gain importance, enhancing its impact on stock price performance (Morgan Stanley 2024; Zairis, Liargovas, and Apostolopoulos 2024). This growing emphasis on sustainability-driven investments highlights the strategic value of EPS in signaling a firm's environmental commitment and effective risk management.

However, an unexpected finding is the significantly negative relationship between the GPS and stock price performance. Governance metrics typically reflect organizational accountability and risk management. The observed negative relationship may suggest a misalignment between the sampled firms’ governance strategies and environmental initiatives. F.e., prioritizing governance practices may divert resources or managerial focus away from environmental improvements, leading to weaker market perceptions (Gök and Sodhi 2021). Alternatively, this result may indicate that investors prioritize environmental performance over governance metrics for decision-making within sustainability-driven market dynamics.

In addition, the significant effect of the control variable current ratio emphasizes the importance of liquidity in maintaining investor confidence. Another noteworthy result is the relatively limited impact of BCCT on the EPS innovation subcategory compared to emissions and resource use. This disparity may arise from the nature of innovation criteria, which often depend on broader organizational strategies beyond the direct impact of BCCT (Zhu et al. 2024). This finding highlights the need for further research to explore how BC can be integrated into broader innovation ecosystems to enhance its role in driving sustainability-related innovation.

Overall, this study provides compelling evidence that BCCT is pivotal in enhancing environmental performance metrics and, consequently, stock price performance. By improving transparency and accuracy in emissions tracing, BCCT enables European retailers to meet stringent environmental standards and signal their commitment to sustainability. EPS thus emerges as a critical mediator in this relationship, serving both as a performance indicator and a communication tool for investors.

4.6. Conclusion

The findings reveal that BCCT can positively impact stock price performance by enhancing the EPS. A higher EPS - driven by transparent and verifiable carbon data - boosts investor confidence and aligns with sustainability-focused market expectations. These findings contribute to a deeper understanding of how BCCT can simultaneously drive sustainability ratings and financial performance, advancing both academic discourse and practical applications of BCCT. However, this relationship depends on the effective implementation of BCCT and accurate communication and education of investors.

4.7. Limitations and Future Research

This section discusses the study's limitations, which may affect the interpretation of its findings, and proposes directions for future research to deepen the understanding of BCCT and its implications.

One key limitation lies in the EPS calculation framework, as not all EPS criteria apply to every company. For instance, firms without biodiversity-related activities are assessed using a reduced subset of criteria. However, all criteria are retained in the classification process, potentially leading to BCCT influencing firms to varying degrees. As a result, the impact of BCCT on the EPS likely depends on a firm's operational scope, a factor that should be considered when interpreting the findings. Another limitation arises from the temporal scope of the data. While the 15-year dataset provides valuable longitudinal insights, ESG reporting standards were less established in earlier years, potentially causing inconsistencies in reported data. These variations are particularly relevant given the rapid evolution of ESG practices and regulations in recent years (Zairis, Liargovas, and Apostolopoulos 2024). Additionally, the study focuses exclusively on publicly listed retailers. While this ensures data availability and facilitates stock price performance analysis, it limits the generalizability of the findings to private firms. Differences in ownership structures, regulatory pressures, and capital market access may lead to divergent sustainability practices and outcomes for private companies, which are beyond the scope of this research. Finally, the unexpected negative relationship between governance scores and stock price performance highlights the complexity of investor behavior, suggesting that unobserved factors may also shape the results and warrant further investigation.

Future research could address these limitations in several ways. First, developing industry-specific EPS frameworks would allow for more precise evaluations of BCCT's impact and clarify why its effects may vary across firms. Longitudinal studies could examine the evolving impact of BCCT as ESG reporting standards mature and regulations become more stringent, offering deeper insights into temporal dynamics and causal relationships. Furthermore, investigating investor perceptions of BCCT - particularly among sustainability-focused funds - could shed light on the mechanisms behind stock price performance.

By addressing these limitations and pursuing these research directions, future studies could provide more robust insights into how BCCT impacts sustainability ratings and financial outcomes.

5. Impact on Firm Performance

After examining BCCT's impact on the four performance metrics - SC performance, purchasing behavior, employee attraction and retention, and stock price performance - this section evaluates their collective impact on overall firm performance.

Supply Chain Performance. Existing research consistently finds that superior SC performance significantly impacts the performance of retail firms (Tarigan, Jiputra, and Siagian 2021; Qrunfleh and Tarafdar 2014). Enhanced SC performance improves information flow, reduces inventory and operating costs, and increases on-time delivery, thereby improving firm performance (Zhang et al. 2006; Rai, Patnayakuni, and Seth 2006; Vonderembse et al. 2006). The four metrics used to measure SC performance underline this relationship. Research shows improved SC efficiency positively impacts firm performance (Daneshvar et al. 2020; Reiner and Hofmann 2006). In addition, SC sustainability has been linked to increased organizational performance, competitive advantage, and knowledge creation (Fabbe-Costes et al. 2014; Govindan et al. 2020; Baah and Jin 2019). SC transparency and improved information sharing positively correlate with operational performance (Bastian and Zentes 2013; Kim, Cavusgil, and Calantone 2006). In addition, SC and stakeholder trust have been found to contribute to improved financial performance (Baah, Acquah, and Ofori 2021; Salam 2017).

Purchasing Behavior. Purchasing behavior plays a pivotal role in driving firm performance. Most directly, purchasing behavior translates into increased sales revenue, which is a fundamental driver of firm performance (Kotler, Keller, and Opresnik 2017). It also serves as a key indicator of a firm's alignment with consumer expectations (Ijabadeniyi and Govender 2019). By analyzing purchasing data, firms can accurately predict the success of marketing campaigns and tailor strategies to maximize conversions and build long-term customer loyalty (Khaniwale 2015). This alignment not only strengthens customer relationships but also optimizes pricing and promotional strategies, ultimately enhancing market competitiveness (Griffith et al. 2009).

However, the findings in Section **Error! Reference source not found.** suggest that BCCT alone is not a “magic bullet” for firms aiming to enhance consumer purchasing behavior and, consequently, firm performance. While BC offers features such as transparency and immutability, its impact on purchasing behavior depends on its integration within a consistent, educational, and credible communication strategy.

Employee Attraction and Retention. Existing literature agrees that the overall effect of employee attraction and retention on firm performance is positive. In the frame of RBV, human resources, such as skilled employees and talented managers, are key assets that drive competitive advantages when they are valuable, rare, inimitable, and non-substitutable (Meyer 1991; Barney 1991). Attracting and retaining such talent strengthens a firm's unique capabilities, particularly in an increasingly skill-dependent global economy (Thurow 1992). More recent research further confirms the positive impact of talent management, including effective attraction and retention, on organizational performance. Regarding attraction, Davids, Button, and Bennett (2018) state that organizations that adopt a well-rounded talent acquisition strategy see improvements in overall performance. These improvements include greater productivity, higher sales, and better customer satisfaction. More generally, with the war for talent, attracting employees has become a challenge, and therefore, enhanced attraction should inherently result in an advantage for the firm (Karunathilaka 2020). Relating to the effect of retention, numerous studies identify the negative impacts of employee turnover, which can be described as the rate at which employees depart an organization over a given period, voluntarily or involuntarily (Price 1977), therefore translating into a positive effect of retention. Hausknecht and Trevor (2011) demonstrate that collective employee turnover can result in negative consequences as it involves losing organization-specific human and social capital, disrupting operations and team dynamics, and driving up recruitment and hiring expenses. Moreover, employee turnover can heighten the risk of knowledge transfer to competitors since employees transition between organizations, potentially exposing key information, which may lead to a loss of market share and profits (Hancock et al. 2013).

Stock Price Performance. The stock price trend is a key indicator of a company's financial health, reflecting market valuation, growth potential, and investor confidence. Positive stock trends signal the firm's ability to generate sustainable profits, attracting institutional and retail investors while improving access to financing on favorable terms (Bird and Casavecchia 2007; Tang 2024). In addition to financial advantages, strong stock price performance facilitates operational improvements. Firms can allocate surplus capital toward research and development, SC optimization, and technological advancements that enhance efficiency and competitiveness (Brown, Fazzari, and Petersen 2009). Lower borrowing costs, driven by investor confidence, also improve cost structures and profit margins, enabling firms to reinvest savings into core operations (Aghion and Stein 2004). Positive stock trends further foster managerial confidence, encouraging long-term strategic planning over short-term profitability measures (Bond and Cummins 2004). This enables firms to pursue sustainable growth initiatives, such as expanding into new markets, ultimately enhancing long-term shareholder value (Aaker and Jacobson 1994).

Overall, all four metrics individually and collectively impact the shared dependent variable, firm performance, paving the way for implications aimed at optimizing outcomes of BCCT implementation.

6. Implications

Based on our findings, this section presents practical implications for European retailers. We synthesize these insights into five dimensions: Stakeholder education and training (Section 6.1), stakeholder communication (Section 6.2), stakeholder collaboration (Section 6.3), operational deployment (Section 6.4), and policy implications (Section 6.5). See Figure 13 for a visualized overview.

6.1. Stakeholder Education and Training

Supplier Training. To successfully integrate BC technology into SCs, it is essential to ensure that suppliers are adequately trained and equipped to operate the technology effectively. Research highlights the importance of comprehensive training programs to enhance collaboration and problem-solving capabilities among SC partners (Manfredsson, Hilletofth, and Reitsma 2019). As emphasized in an industry expert interview, practical training could be implemented through regular webinars and structured meetings (I9). F.e., companies could host virtual workshops to walk suppliers through the process, ensuring they are well-prepared to integrate the technology into their operations.

Consumer Education. While supplier training is key to successful BC technology adoption, companies must also educate consumers to bridge the gap between technological complexity and consumer trust. The study results in Section **Error! Reference source not found.** show that BC usage and the display of carbon data via the QR code do not currently provide the clarity consumers need. Therefore, educational initiatives are vital to improving consumer understanding of BC's role in enhancing data authenticity. As one industry expert states, “There's a need for more education on this topic, which (should be) addressed through social media, advertisements, and websites” (I9). Without adequate understanding, consumers undervalue BC’s role, limiting its ability to influence purchasing behavior (Duong et al. 2024). Educational efforts must focus on illustrating how BC technologies enhance traceability and reliability in ways that are relevant to consumers. Moreover, while BC enhances transparency, it also collects data that may raise concerns about personal information security (Ferreira Da Silva and Moro 2021). Therefore, implementing robust privacy protection is critical as privacy concerns remain a significant barrier to trust in BC technologies, hindering consumer confidence. Educational initiatives must demonstrate the balance between improved transparency and data privacy.

Employee Training. In parallel with supplier and consumer education, companies should introduce internal training programs to ensure their employees understand BC’s functionality and its role in achieving sustainability goals. Without this internal awareness, the potential impact of BC technology - such as strengthening employee retention - may remain unrealized (Law, Hills, and Hau 2015). F.e., interactive e-learning modules could educate employees on how BCCT enhances transparency and supports carbon reduction, fostering a stronger connection to the company’s environmental objectives (Draghici et al. 2021). Targeted training for marketing teams is also critical to enable them to effectively communicate BCCT sustainability benefits to consumers, as the empirical study in Section **Error! Reference source not found.** highlights a lack of awareness in this area. For instance, a company could conduct workshops for marketing staff, focusing on creating campaigns that emphasize their dedication to trace the carbon emissions of their products accurately.

Investor Education. Finally, companies should address investor education to ensure that environmental initiatives gain recognition as drivers of long-term financial value. Despite the growing emphasis on sustainability, as shown in Section 40, industry expert interviews reveal that many investors still fail to incorporate environmental performance into their decision-making processes. According to one industry expert, many investors rarely demand sustainability disclosures as a condition for financing (I1). Although our study positively linked EPS to stock price performance (Section 4.4.2), this indicates a critical gap in further enhancing investors understanding. BCCT advantages can be educated most efficiently by showcasing measurable improvements in environmental performance, particularly as a tool to reduce carbon emissions, alongside tangible financial benefits, like cost savings and increased long-term returns (Strauß 2021). In addition, the positive impact of BCCT on environmental performance should be communicated to investors to ensure they are aware of the positive results. To address this, retailers implementing BCCT should proactively engage with investors through targeted communication strategies, such as sustainability-focused roadshows, investor briefings, and dedicated ESG reporting workshops. By showcasing how initiatives like BCCT improve EPS and financial results, companies can highlight the tangible benefits of environmental performance. Using case studies, data, and projections to link sustainability efforts to efficiencies, compliance, and risk reduction can shift investor perceptions. That helps investors see environmental initiatives as drivers of financial performance and shareholder value, not just tools for regulatory compliance.

6.2. Stakeholder Communication

Effective stakeholder communication is another critical lever for ensuring the successful implementation of BCCT.

Segmenting, Targeting, Positioning. Firstly, the results of the consumer study (Section **Error! Reference source not found.**) show that BCCT's effectiveness is not self-evident and depends on context-specific application and communication. As one industry expert explains, the effect “depends on how you are positioned as a company, what your focus market is” (I7), underscoring the importance of aligning BCCT with market segments, consumer needs, and niches. Market segmentation is critical, as not all consumers prioritize detailed SC information. For instance, different generations prefer distinct sustainability communication approaches: Millennials with higher incomes and education gravitate towards clear carbon-related information, while Generation X relies more on traditional ecolabels (Balcombe et al. 2014; NYU Stern 2023). Retailers should customize marketing strategies accordingly - using tech-forward carbon labeling for younger consumers and familiar sustainability symbols for older demographics who may require educational support. Notably, BCCT also provides reliable environmental data that can serve as a foundation for enhancing the credibility of traditional labels preferred by older consumers. Furthermore, it is essential to use channels that resonate with the target demographic. F.e., it is particularly effective to communicate through social media for younger consumers, as 74% rely on these platforms for decision-making (Forbes 2017).

Positioning BCCT as a trust-building tool is also context-dependent. Research shows that displaying BC-enabled carbon information on a product is particularly effective for companies facing consumer trust deficits, as it can enhance credibility and transparency (Ma, Ma, and Hu 2024). However, for companies with high levels of existing trust, BCCT may add unnecessary complexity and risk alienating their audience. Thus, retailers must carefully assess their market positioning and focus audience to determine whether BCCT implementation will enhance or detract from their value proposition. In addition, retailers can assess the value of BCCT within their product portfolio and implement the technology for specific products where consumers value traceability.

Consumer Sustainability Communication. Secondly, consumers generally favor simple, relatable information over complex data. One industry expert notes that consumers “tend to focus more on (easy) labels, which are concepts everyone can understand" (I9). Overly technical information, such as BC-enabled carbon footprint labels, can overwhelm consumers and foster distrust in the technology (Rapezzi, Pizzi, and Marzocchi 2024; Treiblmaier and Gorbunov 2022) (I4). Instead of showcasing which technology is used to determine the displayed carbon footprint - as done in the survey - simple sustainability labels should be used. This approach could help mitigate the risk of negative perceptions associated with BC (Section **Error! Reference source not found.**).

Sustainability labels are an effective tool for boosting consumer confidence by simplifying the assessment of sustainability information, complemented by the QR Code and numeric footprint on the packaging. However, they must be clear, relevant, and seamlessly integrated into decision-making processes (Iraldo, Griesshammer, and Kahlenborn 2020). For maximum effectiveness, carbon footprint labels should combine categorical, color-coded, and numeric formats, as proposed by Lemken, Zühlsdorf, and Spiller (2021). We recommend stoplight-style labels enabling quick, intuitive comparison (Figure 12). This could help retailers enhance BCCT engagement - and encourage low-carbon choices (Andrews et al. 2014; Holenweger, Stöckli, and Brügger 2023). The QR code should then direct interested users to a clean, easy-to-navigate interface that presents the more detailed carbon data in an accessible, intuitive, and engaging way. According to the Technology Acceptance Model, technology adoption is largely driven by ease of use (Davis, Bagozzi, and Warshaw 1989). A seamless experience can bridge the gap between quick, in-store decision-making and a deeper understanding of sustainability information, ultimately enhancing interaction and purchases.

In addition, consumer trust and perceived transparency are often more closely tied to brand image and effective communication than to specific technological solutions like BC (Foxall, Oliveira-Castro, and Porto 2021). Therefore, storytelling could be a transformative tool in influencing consumer behavior, as narratives help consumers connect with sustainability claims. Stories illustrating positive impacts can make the carbon data more relatable and emotionally engaging. One industry expert stresses consumers need "other evidence to show why the data is trustworthy - maybe a success story" (I5). These should include retailers' commitment to accurately and transparently inform consumers and back this up with stories that personalize the sustainability journey and emotionalize the topic (Navas et al. 2021; Ospital et al. 2023). Similarly, storytelling could enhance employee attraction by strengthening the company's reputation.

In the long term, in contrast to our results from Section **Error! Reference source not found.**, BCCT could then serve as a stimulus for ensuring transparency and fostering complete consumer trust, provided it is supported by effective communication, education, and increased consumer awareness, as these elements align with the technology's capabilities.

Consumer Incentives and Engagement. Thirdly, reward systems and gamification can further enhance the effectiveness of BCCT on purchasing behavior by motivating consumers to make sustainable choices and improving their in-store experience. For instance, QR codes could display cumulative carbon savings, providing a sense of achievement and encouraging more profound engagement. Consumers increasingly seek interactive and immersive retail experiences and respond positively to innovative tools, such as BCCT (Savastano, Barnabei, and Ricotta 2016). Additionally, fostering community building through apps or platforms can create a collective sense of purpose among consumers. Such tools can promote shared sustainability goals, encouraging deeper engagement with the retailer and changing purchasing behaviors (Huang, Su, and Peng 2022). A notable example is Ben & Jerry's pilot program in London, which partnered with Poseidon to offer a platform allowing consumers to offset the carbon footprint of their purchases, combining BCCT with tangible incentives (Smith 2018).

Internal Sustainability Communication. Next, companies should regularly communicate progress on environmental sustainability goals internally to strengthen employee retention. As mentioned in

Section **Error! Reference source not found.**, companies perceived as environmentally responsible benefit from enhanced loyalty and satisfaction among their workforce (Bauer and Aiman-Smith 1996; Rodrigues et al. 2023). Transparent and regular sustainability updates ensure that employees remain aware of their organization's commitment to sustainability, reinforcing alignment with company values, fostering engagement, and bolstering retention through a shared purpose (Cohen et al. 2017; Suazo, Martínez, and Sandoval 2011; Muisyo et al. 2022). In line with P-O fit, this is particularly important for maintaining the loyalty of employees who derive social value from working for an organization aligning with their environmental convictions. Effective communication strategies could include creating dedicated sustainability updates during all-hands meetings, integrating progress reports into internal communication platforms like Slack or Microsoft Teams, or displaying real-time achievements on digital dashboards in shared office spaces.

Investor Sustainability Communication. Lastly, retailers should regularly communicate progress on environmental sustainability goals through external sustainability reporting to strengthen their appeal to investors. By transparently showcasing BC advancements in accurate carbon tracing, emission reductions, and other environmental performance metrics, companies can enhance investor confidence and reinforce their commitment to long-term sustainability (Jian-gang 2011). This communication should highlight measurable achievements, such as improvements in EPS or specific milestones reached through implementing BCCT. As mentioned in Section 4.2, transparent, consistent, and data-driven reporting can position the company as a leader in environmental responsibility, attracting sustainability-focused institutional investors and improving overall market valuation (Schiehll and Kolahgar 2024). Additionally, external communication efforts should be tailored to align with investor priorities, emphasizing financial and environmental outcomes to effectively demonstrate the value of sustainability initiatives in driving long-term growth and reducing risk.

6.3. Stakeholder Collaboration

In addition to communication, collaborating with external stakeholders is crucial.

Supplier Collaboration. First, the successful integration of BCCT into SCs requires the buy-in and collaboration of these partners, which must be secured through effective engagement by fostering long-term supplier relationships (I4, I5). In the next step, to encourage ongoing participation in the BCCT system, companies should emphasize the joint value of the implementation for suppliers and align the incentives of the cooperating organizations (Gutierrez et al. 2020). The former could be done, f.e., by referring to successful outcomes from pilot studies in the area, such as the one by Carrefour (Forde 2019). Another critical approach involves managing stakeholder relationships based on ethical principles and a commitment to addressing stakeholders' interests as ends in themselves rather than as means to an economic goal. Fairness, inclusivity, and long-term responsibility are key aspects of this approach (Kramer, Bitsch, and Hanf 2021). Such ethical stakeholder management could benefit from the transparency and accountability provided by BCCT, helping to build trust and to align partners around shared sustainability goals. F.e., companies could establish joint sustainability committees with supplier representatives to co-create carbon reduction strategies, ensuring all parties have a voice in decision-making and share in the benefits of the process. Similarly, transparent communication is also critical in securing supplier trust. Gutierrez et al. (2020) emphasize that creating a transparent communication and knowledge sharing culture can help build confidence in new processes. Our recommendation to achieve this is the formation of cross-functional teams with regular meetings to update company-external team members.

Collaborative Data Sharing. Building on the importance of fostering trust and transparency in supplier collaboration, an effective approach to data sharing is essential for successful integration. Unlike public BCs, which allow unrestricted data access and may exacerbate suppliers' reluctance to share sensitive information due to fears of revealing competitive product details, consortium BCs (Section 2.4.5) offer a more suitable solution for retailers. By restricting access to authorized participants, consortium BCs alleviate data privacy concerns, enabling retail SCs to release carbon emission-specific data while keeping detailed product information private. Additionally, Consortium BCs are better equipped to handle the complexities of SC structures, offering improved efficiency and faster data sharing, essential for managing intricate networks and processes (Vaigandla et al. 2023; Namasudra and Akkaya 2023). Importantly, this approach preserves carbon data transparency for customers by providing read-only access to high-level carbon emissions insights while protecting sensitive information from public disclosure (Malik, Kanhere, and Jurdak 2018).

Third-Party Service Providers. Companies should also consider collaborating with third-party service providers, such as Aware or Textile Genesis (Table 4), to overcome challenges such as high implementation costs and limited in-house expertise. These providers offer cost-effective solutions, reducing the need for significant upfront investment and simplifying the transition compared to in-house development. Their domain-specific expertise enables companies to optimize BC implementations for energy efficiency, scalability, and security. By outsourcing these operations, companies can focus on core business activities, improving operational efficiency and strategic alignment without the burden of managing complex technical infrastructures. This approach is crucial in the short term, providing immediate solutions while companies can work towards longer-term internal BC development.

Industry-Wide Standardization. Moreover, according to industry experts, an industry-wide solution is essential for large-scale implementation of BCCT in retail (I1, I5, I7, I8, I9). One industry expert claims that "standardized data allows all stakeholders to work from a common platform, simplifying communication, decision-making, and goal alignment across the supply chain" (I2).

To ensure this consistency and simplify emissions reporting, we recommend that retailers working with organizations such as GS1 (I7) establish common metrics and standards for carbon traceability Standardization will reduce complexity for suppliers and increase transparency for consumers (Ehrler et al. 2016). A strong example of this collaborative approach is the Aura Blockchain Consortium, where luxury industry leaders Prada, Cartier, and Louis Vuitton partnered as competitors to develop a BC-based solution for shared challenges like transparency and traceability (Aura Consortium 2022). By opening the platform to all luxury brands, they fostered collaboration and established a unified standard, demonstrating how industry-wide solutions can drive consistency and scale across a sector. These efforts would also be in line with broader EU objectives for harmonized sustainability reporting under initiatives such as the CSRD.

Legislative Advocacy and Lobbying. Finally, retailers could influence the broader policy landscape by actively participating in legislative advocacy and lobbying activities (Guy 2006). Partnering with influential interest groups, such as EuroCommerce and Independent Retail Europe, could amplify retailers' voices in EU decision-making processes. These efforts should prioritize pushing for EU-wide adoption of BCCT, further harmonizing sustainability standards, and establishing financial incentives, such as tax breaks or subsidies for retailers implementing BCCT. Furthermore, we recommend that retailers, particularly those with more significant financial resources, focus on lobbying for increased support under frameworks such as the EGD and lobbying for clear regulatory guidance and removing barriers to BCCT adoption. These actions could help ensure that sustainability requirements are achievable and beneficial for businesses.

6.4. Operational Deployment

Beyond stakeholder collaboration, retailers should also address operational efficiency and technology integration.

Targeted Recruiting. To effectively leverage BCCT to strengthen their workforce, companies should adopt targeted recruitment strategies that align with sustainability goals and attract skilled talent (Shahrulnizam et al. 2024). One approach is to filter for candidates with strong environmental convictions during the recruitment process. Companies could include sustainability-focused questions in interviews or application forms and use scenario-based exercises to assess candidates' environmental values (Das and Dash 2023). F.e., applicants could be asked how they prioritize sustainability in decision-making processes. This would ensure that new hires' values align with the company's commitment to environmental responsibility, fostering long-term retention through enhanced P-O fit and SIT, as outlined in Section **Error! Reference source not found.**. However, this strategy is most effective for companies with well-established or widely perceived environmental responsibility, as employees' values must align with observable practices to have the intended effect (Daqar, Smoudy, and Constantinovits 2019). Furthermore, highlighting sustainability initiatives in recruiting practices is another strategy for attracting talent, as environmental responsibility has been shown to enhance employer attractiveness and JPI (Lis 2012; Behrend, Baker, and Thompson 2009). Companies could achieve this by prominently featuring sustainability initiatives, such as BCCT, on their careers page or creating dedicated recruitment campaigns that showcase progress on carbon reduction goals (Presley, Presley, and Blum 2018). Alternatively, firms could host virtual sustainability webinars for potential candidates, outlining how the company integrates BCCT to meet environmental objectives. Complementing this approach, incorporating green recruitment strategies, such as virtual interviews to reduce travel-related emissions or using paperless application processes, further demonstrates the company's commitment to sustainability, appealing to environmentally conscious applicants (Kiruthigaa and Viswanathan 2014). This effect is particularly strong among younger generations, who are more likely to prioritize sustainability when selecting employers (Duarte, Gomes, and

Neves 2014). To effectively engage younger job seekers, organizations should tailor their messaging to platforms heavily used by this demographic, such as LinkedIn and Indeed, by emphasizing environmental responsibility and related initiatives. Social media platforms like Instagram or TikTok can also serve as effective tools for outreach (Vetráková et al. 2018; Bradford 2018). F.e., short, visually engaging TikTok videos showcasing employees' involvement in sustainability projects or Instagram reels featuring green workplace initiatives could increase JPI among younger candidates. Moreover, attracting talent with the necessary BC expertise to effectively integrate and manage BCCT systems remains a challenge, as highlighted by an industry expert: "I realized that the world of BC is quite small, and the number of people that actually understand it is really small" (Ge et al. 2021) (I6). To address this, companies could adopt targeted recruiting initiatives specifically aimed at IT specialists and BC professionals, such as partnering with universities offering BC-related programs and sponsoring capstone projects or internships to engage students early in their careers. Participation in BC-focused industry events, such as hackathons or conferences, could also help identify skilled candidates while positioning the company as a leader in BC technology. Additionally, posting job openings on niche platforms such as Web3 Jobs or Cryptocurrency Jobs could increase visibility among qualified professionals (Kazakova and Bertulite 2020; Bradel, Steininger, and Veit 2019). Offering competitive learning and development opportunities, such as certifications in advanced BC applications, could further enhance the organization's appeal to this limited talent pool.

Stock Options for Employees. To complement targeted recruitment strategies and enhance employee retention and engagement, retailers could introduce stock option programs tied to environmental and financial performance metrics. By offering employees a stake in the company's success through stock options, firms create a direct link between individual contributions, sustainability achievements, and financial rewards (Oyer and Schaefer 2005). These programs should align stock options with BCCT-driven key performance indicators, such as improvements in EPS, carbon footprint reductions, or other measurable sustainability targets, aligning employee efforts with both short-term operational objectives and long-term sustainability strategies (Ammel, Boyer-Davis, and Karki 2024). By tying compensation directly to sustainability and financial performance, firms can foster a sense of ownership and loyalty, strengthen their ability to attract top talent and reinforce their commitment to environmental innovation, ultimately driving improved employee engagement and retention (Felo et al. 2015).

EU Funding Opportunities. Beyond workforce considerations, companies should leverage external support to accelerate BCCT implementation, such as tapping into the EU's research and innovation funding programs, designed to accelerate the transition to a greener future. Initiatives like Horizon Europe support projects like the European Blockchain Services Infrastructure (EBSI) (European Commission 2024b). To this date, €347 million in EU funding has been allocated to BC-related research and innovation, underscoring its significance in meeting Europe's environmental and technological goals (European Commission 2022b). We recommend that retailers actively seek out these programmes and apply for funding to gain additional resources to implement BCCT.

Integration with Complementary Technologies. While funding supports BCCT implementation, its operational effectiveness can be further enhanced through the integration of complementary technologies. Combining BC with emerging solutions such as IoT, AI, and satellite systems can address existing challenges, like ensuring the upload of supplier data, particularly its accuracy. IoT sensors can autonomously collect real-time product data and automatically feed it to AI systems, which then calculate emissions directly (Section 2.4.7). This approach potentially eliminates the need for traditional LCA tools, streamlining the entire process. In addition, satellite data can increase the accessibility of carbon data up to the agricultural level (I6). An interconnected ecosystem facilitated by Application Programming Interface integration would enable these technologies to work collaboratively, automating data collection, analysis, and decision-making (I6). Studies by Naranjo, Espinoza, and Vivar (2023) and Suji Priya et al. (2023) support this model, demonstrating that such technological integration improves efficiency, enhances data security, reduces fraud risks, and promotes greater operational transparency. However, BCCT adoption is already challenging long-established retail SC processes, and integrating additional technologies could further complicate this transformative journey.

Energy-efficient Solutions. While integrating BC with complementary technologies can enhance operational efficiency, energy considerations remain. As environmental measures mediate the relationship between BCCT, talent attraction and retention, and stock price performance, adopting energy-efficient solutions is essential to impact firm performance positively. To address this, Sedlmeir et al. (2020) argue that adopting alternative BC designs, such as the PoS mechanism instead of the energy-intensive PoW (Section 2.4.4), can substantially mitigate BC's environmental concerns. Second, we recommend integrating edge and cloud computing to reduce the computational burden on BC nodes, improving energy efficiency without sacrificing performance (Goel et al. 2024). Third, by collaborating with third-party service providers, energy concerns related to BC can be mitigated. Textile Genesis, f.e., leverages BC's core principles by implementing a secure, transparent, and immutable digital ledger that traces textile SCs, utilizing digital tokens generated at the material's origin to ensure traceability while avoiding energy-intensive PoW consensus mechanisms.

Piloting. Above all, piloting is essential before scaling up to ensure a smooth operational deployment of BCCT. Hoek (2019) confirms this by highlighting the importance of targeted BC pilots in SCs to evaluate feasibility, costs, and benefits, drawing lessons from early adopters in logistics, consumer products, and retail industries. As already mentioned, Walmart piloted BCCT with mangoes in the U.S. and pork in China, collaborating with IBM for technology implementation, also demonstrating the value of third-party providers (Tan et al. 2018; Sharma and Kumar 2021). Furthermore, we recommend that BCCT be trialed within regional SCs to reduce complexity and minimize the need for extensive process changes. Focusing on a specific product category could further simplify pilots while generating insights applicable to other segments. Lastly, stakeholder buy-in throughout this process is crucial, as mentioned above.

6.5. Policy Implications

While the primary focus of this study is on firm-level implications, we also highlight key governmental policy recommendations to support and accelerate BCCT adoption.

Consumer Awareness Campaigns. Policymakers should invest in nationwide consumer education initiatives to raise awareness of the environmental benefits of BCCT. An industry expert underscores this: “There's a need for more education on this topic, which we address… . But other actors, like the state, schools, and universities, also play a role in educating the public“ (I9). Governmental campaigns could be integrated into broader government sustainability efforts, such as those under the European Climate Pact, an EU initiative aimed at collective action toward achieving a climate-neutral Europe by 2050. Additionally, governments could support creating engaging media content - such as documentaries, podcasts, or social media campaigns - showcasing real-world examples of how BCCT enhances transparency, which promotes sustainability in the retail sector and facilitates compliance.

Government Incentives. To accelerate the adoption and implementation of BCCT, policymakers should introduce targeted financial mechanisms designed to reduce entry barriers and drive performance improvements. F.e., subsidies could cover initial implementation costs to some extent (EEG 2023). Tax credits could be offered to companies that achieve verified emissions reductions using BCCT, encouraging uptake and sustainable performance improvements. These financial instruments would be aligned with broader EU decarbonization goals related to the EGD. These incentives should be conditional on compliance with standardized reporting frameworks and measurable decarbonization outcomes to maximize impact.

7. Conclusion

This thesis analyzes how BCCT impacts SC performance, purchasing behavior, employee attraction and retention, and stock price performance, ultimately contributing to overall firm performance in the European retail sector.

The findings reveal that BCCT enhances the four considered SC metrics: efficiency, transparency, trust, and sustainability. However, these effects rely on the presence of specific enablers identified in expert interviews, namely Supplier Education, Industry-wide Standardization, Integration with Complementary Technologies, and Long-term Supplier Relationships. Assuming these enablers are in place, the enhanced SC metrics positively impac firm performance, with SC performance acting as a mediator.

Regarding purchasing behavior, BCCT does not currently appear to affect this variable, either directly or mediated by perceived transparency or consumer trust. Nevertheless, perceived transparency and trust independently drive purchase intentions, suggesting that consumer education and effective communication on the actual benefits of BCCT could narrow the gap between actual and perceived effects. This could eventually result in a positive impact on purchase intentions, which would, in turn, enhance firm performance.

The findings also indicate that BCCT impacts employee attraction and retention by enhancing the firm's environmental responsibility. Since attraction and retention contribute to firm performance, BCCT indirectly enhances firm performance through its impact on environmental responsibility.

This effect is particularly strong among younger generations and individuals with strong ecological values.

Furthermore, BCCT can positively impact a company's EPS, which, in turn, shows a statistically significant positive relationship with stock prices over the past 15 years. By improving environmental valuation, BCCT may indirectly boost overall company performance.

In response to the umbrella RQ, this thesis concludes that BCCT can positively impact the performance of European retailers. This impact is observed across four key areas: SC performance, purchasing behavior, employee attraction and retention, and stock price performance. However, the impact level depends on Stakeholder Education and Training, Stakeholder Communication, Stakeholder Collaboration, and Operational Deployment, as outlined in the preceding section. Additionally, we suggest two policy implications, recognizing that incentives from the public sector also play a crucial role in the success of BCCT.

This thesis contributes not only to a more comprehensive understanding of effective BCCT in the European retail sector but also supports alignment with EU mandates to ultimately become the world’s first climate-neutral continent by 2050.

8. Limitations and Future Research

This section discusses the limitations of this thesis, addressing constraints in scope, methodology, and analysis that impact the comprehensiveness and generalizability of the findings.

Narrow Focus of Metrics. This thesis evaluates the impact of BCCT on four performance metrics. While this provides a comprehensive framework, the scope is naturally limited due to the size of our research group, consisting of only four members. Consequently, other potentially critical areas, such as innovation performance, are not directly addressed, even though they might offer valuable insights. To address this limitation, future research should incorporate further performance dimensions to provide a more holistic approach to understanding BCCT's impact on firms.

Use of Mediators. The analysis relies on mediated relationships to evaluate the impact of BCCT on stock price performance, consumer purchase intention, and talent attraction and retention. While this approach is widely accepted in academic research and supported by theoretical and empirical evidence, it does not establish direct causal links. Consequently, other unmeasured factors may influence the mediators. Future research could aim to isolate and directly measure these effects to enhance the robustness and conclusiveness of the findings.

Focus on Application of Technology. This thesis examines the application of BCCT in the retail sector; however, it does not delve into the technical development of BC systems, such as algorithms, coding structures, or smart contract design. Future research should address these technical aspects to uncover potential constraints and enhance the optimization of BCCT implementation.

Heterogeneity of Retailers. The recommendations are generalized to address challenges across the European retail sector but may not fully account for the specific needs of individual retailers. Even touched upon briefly, differences in company size, resource availability, technological infrastructure, and market positioning may affect the feasibility and effectiveness of these recommendations. Future research could focus on creating more tailored strategies that align with diverse organizational capabilities and market conditions.

Lack of Quantification of Performance Impact. Although this thesis evaluates the impact of BCCT across four key metrics, it does not include a quantitative assessment of firm performance. The analysis focuses on qualitative insights and theoretical frameworks, leaving the magnitude of the effects unmeasured, as this would exceed the scope of the thesis. This limitation restricts the ability to compare the benefits of BCCT adoption against its costs or to evaluate its return on investment in measurable terms. Future research should incorporate quantitative methods, such as cost-benefit analysis or performance metrics modeling, to provide a clearer picture of the tangible impacts of BCCT on firm performance.

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List of abbreviations

BC	Blockchain
BCCT	Blockchain-enabled Carbon Traceability
CSRD	Corporate Sustainability Reporting Directive
EGD	European Green Deal
EPS	Environmental Pillar Score
ESG	Environmental, Social, and Governance
GHG	Greenhouse gas
JPI	Job Pursuit Intentions
LCA	Life Cycle Assessment
MRV	Monitoring, Reporting, and Verification
P-O	Person-Organization
PoS	Proof-of-Stake
PoW	Proof-of-Work
RBV	Resource-based View
RQ	Research Question
SC	Supply Chain
SIT	Social Identity Theory
SOR	Stimulus-Organism-Response
VIF	Variance Inflation Factor

Appendix A

Figure 3. *Research Methodology Overview.*

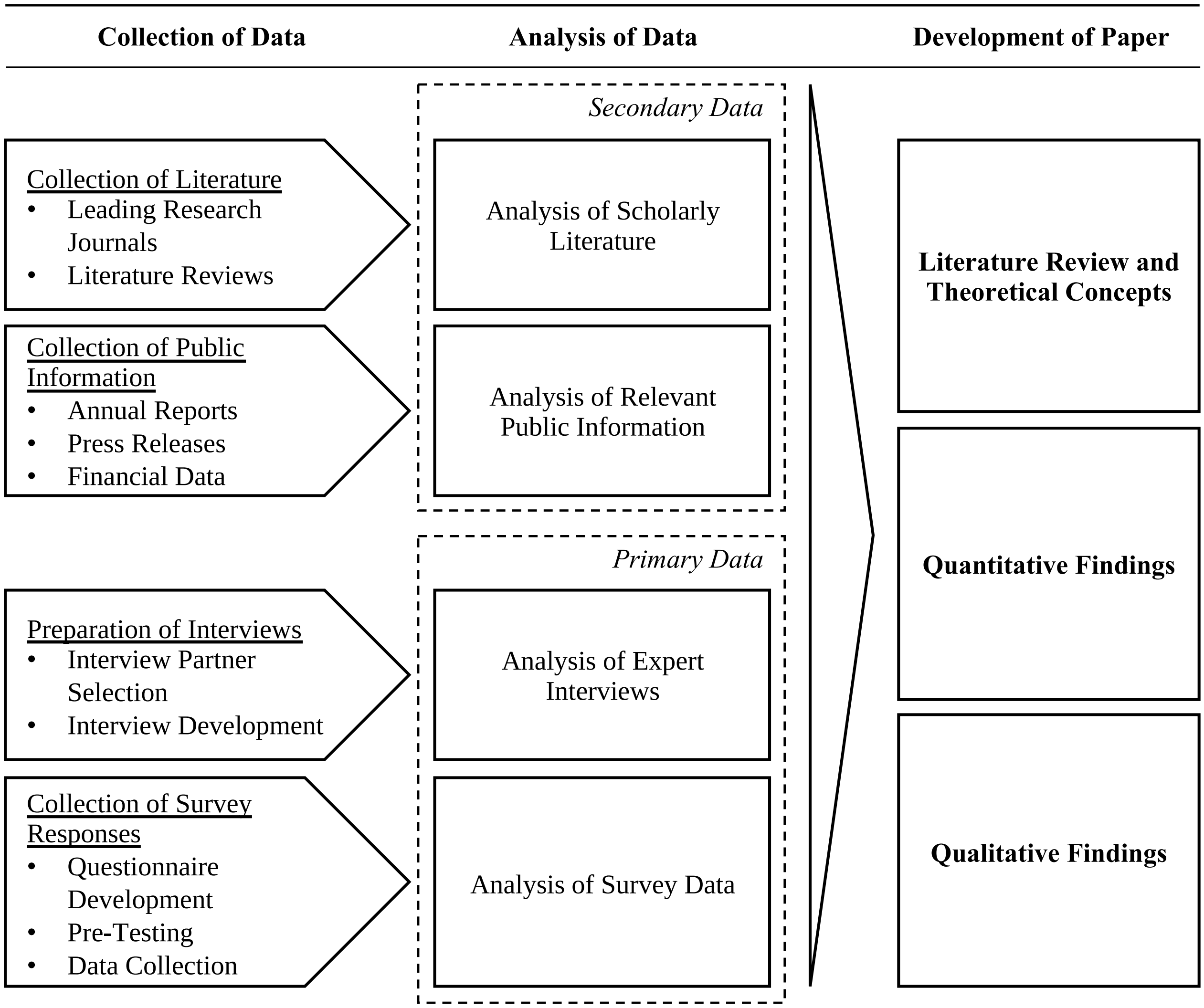

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Figure 4. Conceptual Model of BCCT Impact on Supply Chain Performance.

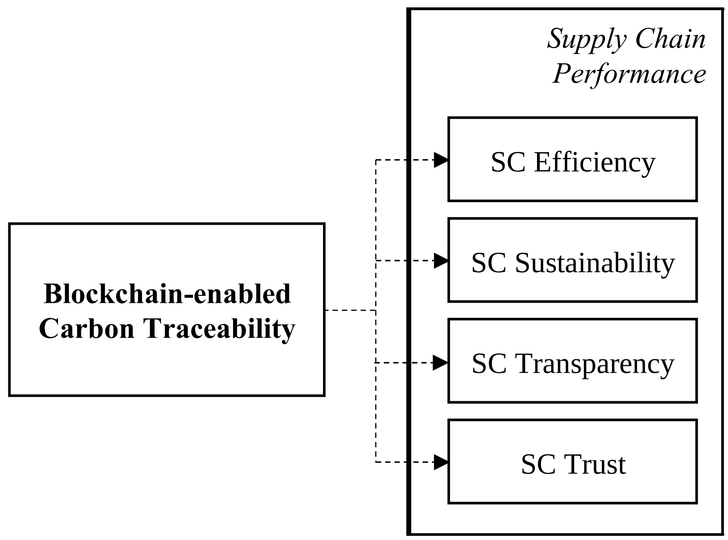

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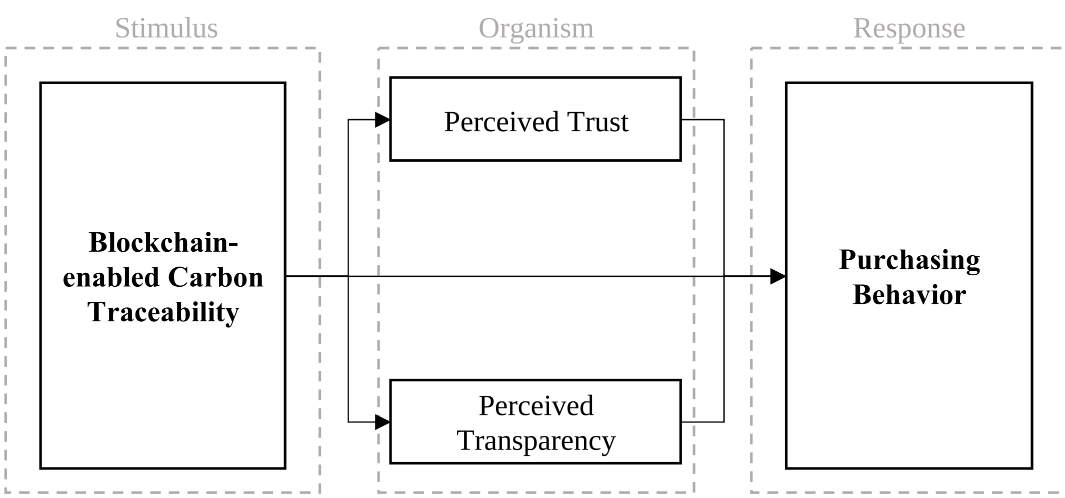
Figure 5. Conceptual Model of BCCT Impact on Purchasing Behavior.



Note: Adapted from Theory of Planned Behaviour and SOR Model.

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Figure 6. *Stimulus Shown to the BCCT Group in the Survey.*

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Figure 7. Stimulus Shown to the Non-BCCT Group (Control Group) in the Survey.

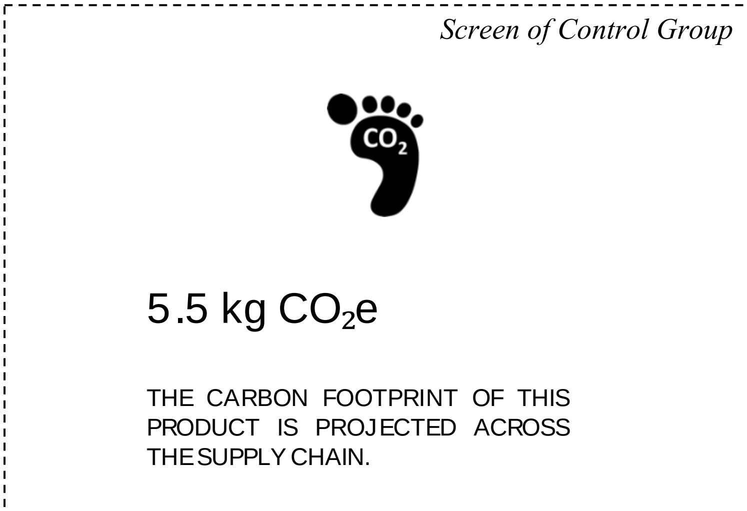

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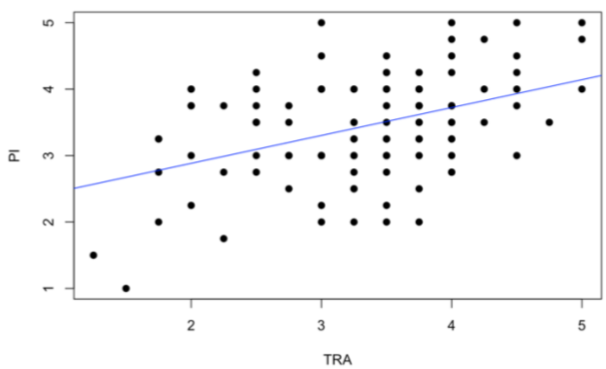
Figure 8. Linearity Assumption (Example Transparency).



The *linearity assumption* tests whether there is a linear relationship between the independent variable (Transparency) and the dependent variable (Purchase Intention). The scatterplot shows that the data points align reasonably well around the regression line. This indicates that the relationship between Transparency and Purchase Intention is approximately linear. However, some variability in the scatter of the points, particularly at the lower and upper ends of Transparency, suggests that further inspection for outliers or transformations may be useful. Using the outlier test in R, observation 55 is identified as having the largest studentized residual. However, the

Bonferroni-corrected p-value indicated that this observation is not a statistically significant outlier. Therefore, it is not necessary to exclude any data points from the analysis.

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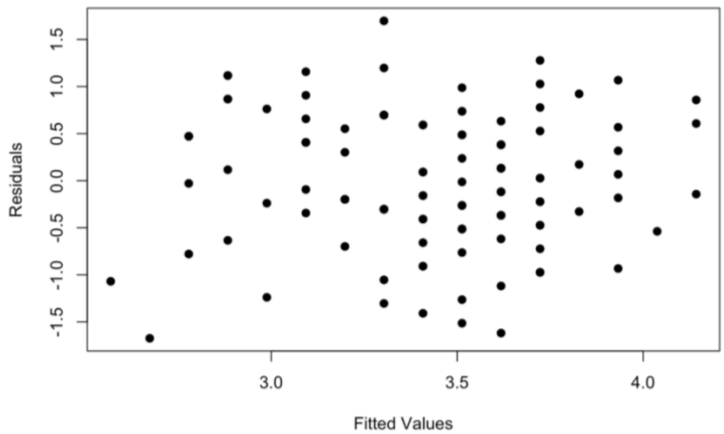
Figure 9. *Homoscedasticity Assumption (Example Transparency)*



Homoscedasticity assumes that the residuals have constant variance across all levels of the fitted values (predicted Purchase Intention values). The residual plot shows residuals that appear randomly scattered around zero without a discernible pattern. This indicates that the variance of the residuals is roughly constant, and the homoscedasticity assumption is likely met. No evidence of heteroscedasticity (e.g., cone shapes or clustering) is observed.

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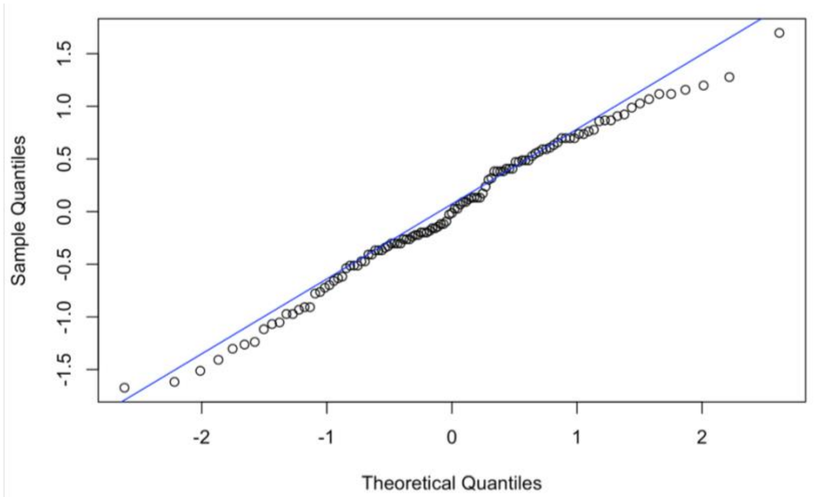
Figure 10. *Normality of Residuals (Example Normal Q-Q Plot for Transparency)*



Normality assumes that the residuals are normally distributed, which is important for valid hypothesis testing and confidence intervals. The Q-Q plot ("Normal Q-Q Plot of Residuals for Transparency") shows that the residuals mostly align along the diagonal reference line, indicating that they are approximately normally distributed. Minor deviations at the tails are visible but are not extreme, suggesting no major violations of the normality assumption.

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Figure 11. *Conceptual Model of BCCT Impact on Stock Price Performance.*

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Figure 12*. Visualisation of Stoplight Implementation.*

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Figure 13. *Visualization of Implications.*

Stakeholder Education and Training

- Supplier Training
- Consumer Education
- Employee Training
- Investor Education

Stakeholder Communication

- Segmenting, Targeting, Positioning
- Consumer Sustainability Communication
- Consumer Incentive Engagement
- Internal Sustainability Communication
- Investor Sustainability Communication

Stakeholder Collaboration

- Supplier Collaboration
- Collaborative Data Sharing
- Third-party Service Provider
- Industry-Wide Standardization
- Legislative Advocacy and Lobbying

Operational Deployment

- Targeted Recruitment
- Stock Options for Employees
- EU Funding Opportunities
- Integration with Complementary Technologies
- Energy-efficient Solutions
- Piloting

Policy Implications

- Consumer Awareness Campaigns
- Governmental Incentives

Click here to return to Section 6.

Appendix B

Table 1. Semi-structured Interview Guide.

Introduction
Thank you for agreeing to participate in this interview. My name is Alexander Ritter, and this interview is part of my master's thesis research at the Nova School of Business and Economics. With increasing sustainability requirements and EU regulations such as the EGD and the Carbon Border Adjustment Mechanism forcing companies to prioritize carbon traceability, I am investigating how blockchain-enabled carbon traceability influences supply chain performance in the retail sector, focusing on metrics such as efficiency, transparency, trust, and sustainability. The interview will take approximately 30-40 minutes. Your responses will be kept confidential, and we can provide a non-disclosure agreement if needed. Is it also okay to record this interview? Any questions before we begin?

Topics/Subtopics	**Questions**
Introductionary Question	1. Could you please introduce yourself, Company X and you role at Company X?
Topic 1: Current Standpoint	1. What is your experience with carbon traceability within retail supply chains? 2. What is your perspective on the current state of blockchain adoption for carbon tracing in the retail sector? 3. Scholars have pointed out the challenges of tracing Scope 3 emissions, data fragmentation, and varying stakeholder demands associated with carbon traceability in retail. How would you describe the role of blockchain in addressing these unique challenges?
Topic 2: Efficiency	1. What are your thoughts on blockchain's potential to improve efficiency in carbon tracing within retail supply chains? 2. In your experience, how does blockchain impact the speed and cost of tracing carbon emissions across multi-tier retail supply chains? 3. Do you believe the efficiency gains from blockchain can outweigh the initial investment and operational costs involved? Why or why not?
Topic 3: Transparancy	1. Transparency is often cited as a key advantage of blockchain. How do you see this feature benefiting carbon traceability in retail supply chains? 2. How do you think blockchain transparency impacts the accuracy and availability of carbon data between partners? 3. Some academics argue that despite its transparency, blockchain may lack incentives for certain regions (e.g. Asia) to share accurate carbon data. Do you see this as a limitation for retail supply chains?
Topic 4: Trust	1. Trust is crucial in sharing and verifying carbon data across multi-tiered supply chains. How do you think blockchain's immutability affects trust in carbon tracing for retail? 2. Smart Contracts are another aspect of blockchain that can strengthen partnerships by automating agreements and reducing opportunistic behavior. What role do Smart Contracts play in maintaining trust and collaboration in carbon tracing within retail supply chains?

	3. Blockchain technology may still allow for data misrepresentation due to a lack of motivation for accurate data entry. Do you think that blockchain alone can sufficiently address trust issues related to carbon data accuracy and reporting? Or are complementary technologies needed?
Topic 5: Sustainability	1. What role do you see blockchain playing in supporting retail companies' sustainability goals, especially concerning carbon neutrality? 2. How well do you think blockchain can support retail companies in meeting regulatory compliance requirements from the EU related to carbon tracing and sustainability? 3. Blockchain's energy consumption is often a concern. Do you believe this affects its viability as a tool for promoting sustainability in carbon tracing?
Final Considerations	1. What are the main barriers to implementing blockchain for carbon traceability in the retail sector? 2. Do you think other technologies should complement blockchain to improve carbon traceability or is blockchain alone sufficient? 3. Are there any specific areas within blockchain-enabled carbon tracing that need more research to understand its impact on retail supply chain performance?

Concluding Remarks
Before we wrap up, is there anything else you'd like to add, or are there any other resources or experts you'd recommend I consult on this topic? Thank you so much for sharing your insights today, I really appreciate you taking the time! If you are interested, I would be happy to share a summary of the findings once the research is complete. Additionally, if I have any follow-up questions or need clarification, would it be okay to reach out? Just a reminder that all of your responses will be kept confidential, and any information you provided will be anonymized in my report. Thank you once again, this has been incredibly helpful for my research. Have a great day!

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Table 2. *List of Industry Experts outreached.*

Name	Organization	Position
Christina Rechtsteiner	Munich Electrification	Sustainability Manager
Jelena Nicolic	Deutscher Handelsverband	Head of CSR
João Joanaz de Melo	Nova Professor	Research sustainability assessment
Sahil Baxi	Carbon Chronicles	Founder
Lukas Stumpf	Höveler Holzmann	Nachhaltigkeit in SCM Beratung
Elhoussaine Hosny Wahyana	Université Rabat	PhD Enhancing Supply Chain Sustainability with Blockchain
Ayrton Dhillon	KPMG London	Capital Program Manager
Niccolò Corsini	Logidot	Founder/CEO @ LOGIDOT | Advisory Board Member | Investor
Pavels Sidlovskis	Arcadis	Arcadis
Jessie Brenner	Textile Genesis	Sustainability Strategist | Material Expert
Merel Krebbers	H&M	Director of Solutions Management: Traceability, Compliance and Packaging
Concepción Galdon PhD.	IE Business School	Vice-Dean Business with Purpose (IE Business School)
Olivia de Seze	Aware	Business Development Representative
Lars Kreuchwig	Coca-Cola	BPT Business Partner - PAC & Sustainability
Sophie Van Kol	Fashionforgood	Innovation Manager
Aljosha Rix	GS1	Junior Manager Supply Chain Management
Solenne Zandronis	Wildling Shoes	Supply Chain Sustainability Specialist - Social Impact & Traceability
Alex van der Heyden	Inditex	Sustainability Specialist at Bershka
Rachelle Graham	IKEA	Traceability Leader
Aya Abdelaziz	GS1	Global Sustainability Programme - Capabilities
Koen Warmerdam	Aware	Co-Founder
Tom Weijtmans	VeChain	Community Ambassador
Natalia Montaña	Loewe	Sustainability Compliance & Traceability Specialist
Axel von der Heyden	Inditex	Sustainability Specialist
Aled Davies	Finboot	Technical Lead

Padma Raj Keshri	Ralph Lauren	Regional Sourcing Manager, Traceability
Paola Braione	Richemont	Responsible Sourcing Specialist
Erin Finley	Walmart	Supply Chain Manager
Sophia Burathoki	Walmart	Associate Director, E2E Supply Chain
Sonia Strate	Walmart	Senior Supply Chain Manager
Sahil Bhosale	Walmart	Director, Omnichannel Supply Chain Strategy and Transformation
Niki Lewis	Bext360	Chief Sustainability Officer
Dean Kingston	Bext360	Founder and COO
Daniel Jones	Bext360	Founder and CEO
Karl Bedwell	CPS	Executive Vice President and Chief Information Officer
Surabhi A.	Starbucks	Group Product Manager, Strategy & Innovation
Sébastien Vincent	Louis Vuitton	Traceability & Blockchain Domain Leader
Claudia Lee	Crystalchain	Chef de projet traçabilité
Andreas Weckwert	Nature Office	CEO
Taouifik Manar	Hermès	Supply Chain Traceability Program - IT Manager
Julia Menge	ICF	Lead Management Consultant - Sustainable Finance and Climate Policy
Valeriia Dicken	ALDI SÜD	National Sustainability
(Hoek 2019)	Project Trick	Any
Leonie von Holtz	ALDI SÜD	Specialist Sustainability - Climate
Markus Pawelski	CAS AG	Solution Owner Supplier & Customer Interaction – Retail
Julia Pötsch & Markus Hau	Nestlé	Europe & Supply Chain Director; International Customers & Digital Supply Sales Sustainability Lead Chain

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Table 3. *List of Industry Experts interviewed.*

Name	Organization	Position	ID
Christina Rechtsteiner	Munich Electrification	Sustainability Manager	I1
Sahil Baxi	Carbon Chronicles	Founder	I2
Jessie Brenner	Textile Genesis	Sustainability Strategist/ Material Expert	I3
Olivia de Seze	Aware	Business Development Representative	I4
Lars Kreuchwig*	Coca-Cola	BPT Business Partner - PAC & Sustainability	I5
Sophie Van Kol	Fashionforgood	Innovation Manager	I6
Aljosha Rix	GS1	Junior Manager Supply Chain Management	I7
Solenne Zandronis	Wildling Shoes	Supply Chain Sustainability Specialist - Social Impact & Traceability	I8
Leonie von Holtz & Valeriia Dicken*	ALDI SÜD	Specialist Sustainability - Climate	I9
Markus Pawelski	CAS AG	Solution Owner Supplier & Customer Interaction – Retail	I10
Julia Pötsch & Markus Hau*	Nestlé	Europe & Supply Chain Director; International Customers & Digital Supply Sales Sustainability Lead Chain	I11

*Note: *Expert opinion does not equal company opinion*

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Table 4. *Overview third-party service providers interviewed.*

	Textile Genesis (I3)	**Aware (I4)**
Website	https://textilegenesis.com/	https://news.wearaware.co/
About	TextileGenesis™ is an innovative platform that aims to revolutionize traceability in the fashion and textile industry.	Aware™ combines physical tracer technology with public blockchain technology to deliver reliable and transparent traceability.Their BC enables full traceability of sustainable materials from the fiber level to the finished product utilizing .
Traceability	TextileGenesis uses a fiber-forward traceability approach, leveraging blockchain principles to ensure transparent and reliable tracing of materials: **Fiber Coins**: Digital tokens created at the origin of the material, tracing materials throughout the supply chain to prevent over-claiming and ensure ESG compliance. Traceability Modules: **Fiber to Retail**: Robust tracing of sustainable materials from origin to finished product. **Supply Chain Discovery**: Product backward self-declaration for conventional and sustainable materials. **Supply Chain Mapping**: Simplified mapping for complex categories such as footwear and leather. **AI Integration**: Calculates waste and loss, ensuring material accountability and accurate tracing. This system provides brands with end-to-end traceability and compliance for all material types.	Unlike traditional traceability solutions that work backwards from the finished product, Aware starts at the source-whether it's organic cotton from the field or recycled materials from the factory. Two-Track Traceability: 1. **Digital Platform**: The platform tokenizes materials (e.g., 1 kg of recycled polyester = 1 token) and traces them through the supply chain using a mass balance system. It connects all stakeholders, from spinners to brands, and links material data to the final product via a digital product passport. This passport records compliance (e.g. environmental, social, chemical) and meets global regulations. 2. **Physical Tracer**: A secure, embedded modified ceramic tracer ("like powdered sugar or glass") is added during spinning or ginning. It can be verified with a hand scanner, ensuring authenticity throughout the supply chain. The tracer is safe, invisible and doesn't change the properties of the material.

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Table 5. *Measurement Scales and Reliability (Purchasing Intention Regression).*

Variable (adapted from)	**Cronbach's Alpha**	**Questions**	**Factor Loading**
Perceived Transparency (Montecchi et al. 2024; Fraser and van der Ven 2022; Sodhi and Tang 2019)	0,759	I believe the retailer is being transparent and open about the product's carbon footprint.	0,547
		I can trace the carbon footprint of the product easily.	0,757
		The carbon emission information provided by the company is reliable.	0,521
		The information provided about carbon emissions is clear and detailed.	0,688
Consumer Trust (Navas et al. 2021; Doney and Cannon 1997)	0,782	I am certain that the information about the carbon footprint provided by the retailer is correct.	0,559
		I trust the retailer to provide accurate information.	0,719
		The retailer is being honest.	0,763
Purchase Intention (Navas et al. 2021; L. Zhou et al. 2018)	0,747	I would consider purchasing the product from this retailer, based on given information.	0,645
		I would rather recommend this product to others than without a label.	0,554
		The information about the carbon footprint is useful for informing my purchasing decisions.	0,663
		I would expect to buy the product with this form of carbon information.	0,583

Notes: All factor loadings are significant on a 0.01 level.
All variables ranging from 1 (Strongly Disagree) to 5 (Strongly agree).

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Table 6. *Pearson Correlations (Purchasing Intention Regression).*

	1	2	3	4
1 Transparency	1			
2 Trust	0.511***	1		
3 Purchase Intention	0.428***	0.474***	1	
4 BCCT Group	-0.017 (n.s.)	-0.066 (n.s.)	-0.152 (n.s.)	1

*Notes: * p<0.05, ** p<0.01, *** p<0.001*

Multicollinearity. The Pearson correlation between Transparency and Trust is 0.511, which indicates a moderate relationship and raised the possibility of multicollinearity. To further investigate, we calculated the VIF for these variables. The values for both Transparency (VIF=1.354) and Trust (VIF=1.360) are well below the commonly accepted threshold of 5, confirming that multicollinearity is not an issue in this model. Therefore, both variables can be included in the analysis without compromising the reliability of the results.

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Table 7. *Manipulation Check Test (Purchasing Intention Regression).*

	Mean	BCCT Mean	Non-BCCT Mean
Perceived Transparency	3,316	3,301	3,328
Trust	3,174	3,116	3,219
Purchase Intention	3,436	3,301	3,539

A two-way MANOVA is conducted to examine the effect of BCCT (BCCT: 1.00 = BC-enabled, 0.00 = Non-BCCT) on perceived transparency and trust. The results indicate no statistically significant main effect of BCCT Group on the combined dependent variables. Descriptive statistics showed that participants in the BCCT condition reported slightly lower perceived transparency (M=3.30, SD=0.77) compared to the non-BCCT condition (M=3.33, SD=0.82). Similarly, perceived trust is marginally lower in the BCCT condition (M=3.12, SD=0.65) compared to the non-BCCT condition (M=3.22, SD=0.86). Purchase intention is also slightly lower in the BCCT condition (M = 3.30, SD = 0.78) compared to the non-BCCT condition (M = 3.54, SD = 0.81). However, these differences are not statistically significant.

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Table 8. *Levene's Test for SD (Purchasing Intention Regression).*

	SD	BCCT SD	Non-BCCT SD
Perceived Transparency	0,797	0,769	0,824
Trust	0,777	0,651	0,863
Purchase Intention	0,781	0,834	0,728

Results. The BCCT group consistently shows slightly lower standard deviations across all variables, indicating less variability in participants' responses compared to the non-BCCT group. The difference in standard deviations for trust is statistically significant at the 0.05 level. The p-value for Levene's test for Trust is 0.034, which is below the 0.05 threshold. This indicates that the variability in trust differs significantly between the BCCT and Non-BCCT groups. For the other variables (perceived transparency and purchase intention), the differences in variances are not statistically significant.

Discussion. For managers in the retail industry, these results highlight BC technology's potential to stabilize trust levels among consumers, fostering more predictable customer relationships. While trust variability is lower in the BCCT group, it is important to note that the mean trust level remains higher in the Non-BCCT group. This suggests that while BCCT promotes consistency, it may not always lead to higher overall trust. To achieve both higher and more consistent trust, managers should implement necessary enablers such as clear communication, user education, and complementary transparency measures alongside BCCT.

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Table 9. *Coefficients (Purchasing Intention Regression).*

Coefficients	Estimate	Standardized	Std. Error	t	p
(Intercept)	1,541	NA	0,400	3,850	<0.001
TRA	0,257	0,262	0,091	2,826	0,006
TRU	0,309	0,307	0,094	3,281	0,001
BCCT Group	-0,250	-0,159	0,128	-1,953	0,053
Age	-0,066	-0,113	0,050	-1,327	0,187
Gender	0,259	0,183	0,118	2,200	0,030
Education	-0,005	-0,007	0,064851	-0,084	0,933

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Table 10. *ESG Calculation and Structure.*

Elements	Weight
ESG Score	100,0%
Environmental Pillar Score	23,0%
Social Pillar Score	49,3%
Governance Pillar Score	27,7%

Elements	Weight
Environmental Pillar Score	23,0%
Resource Use	3,7%
Emission	5,5%
Innovation	13,8%

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Table 11. *EPS Criteria Classification.*

Dimension	Count	Share
Directly affected	70	23,5%
Resource Use	*7*	
Emission	*62*	
Innovation	*1*	
Indirectly affected	89	29,9%
Resource Use	*32*	
Emission	*33*	
Innovation	*24*	
Not affected	139	46,6%
Resource Use	*18*	
Emission	*101*	
Innovation	*20*	
Total	298	100,0%

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Table 12. *Model Summary (Stock Price Performance Regression).*

R	R^2	Adjusted R^2	RMSE	F	p
0,528	0,279	0,248	147,718	9.079	< 0.001

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Table 13. *Descriptive Statistics (Stock Price Performance Regression).*

	E Score	S Score	G Score	Employees	Revenue	ROA	Earnings	Current Ratio
Median	59.895	66.215	51.955	26.884	1.509E+08	5.505E+05	1.261E+07	1.340
Mean	58.678	63.158	50.920	4316.241	3.517E+09	5.215E+07	8.977E+08	2.795
Std. Deviation	24.287	23.110	22.454	29803.562	1.775E+10	3.815E+08	7.173E+09	37.380
Skewness	-0.317	-0.614	-0.138	13.827	10.470	3.752	9.909	55.986
Std. Error of Skewness	0.069	0.068	0.068	0.068	0.030	0.123	0.031	0.030
Kurtosis	-0.745	-0.381	-0.896	255.253	134.308	72.907	182.729	3314.725
Std. Error of Kurtosis	0.137	0.136	0.136	0.136	0.060	0.246	0.061	0.060

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Table 14. *Coefficients (Stock Price Performance Regression).*

	Standard Error	**Standardized**	**t**	**p**
(Intercept)	59,816		-2,932	0,004
E Score	0,738	0.94	2,399	0,017
S Score	0,704	0,117	1,343	0,181
G Score	0,639	-0,226	-3,119	0,002
Employees	0,001	0,041	0,588	0,557
Revenue	<0.001	0,381	2,103	0,037
ROA	<0.001	-0,024	-0,280	0,780
Earnings	<0.001	-0,339	-1,705	0,090
Current Ratio	17,343	0,475	7,126	<0.001

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