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APPLYING DIGITAL TECHNOLOGIES TO SUSTAINABLE DELIVERY OF GOODS *

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Received 15 October 2025; accepted 20 February 2025; published 30 March 2025

Abstract. This study explores how digital transformation drives sustainable practices in supply chains and related industries. The objectives focus on examining the integration of advanced digital technologies – to enhance environmental sustainability in logistics and production systems. Methodologically, the research analyses current literature and industry cases to identify key mechanisms and outcomes of digital initiatives. Key findings indicate that digital transformation significantly improves resource efficiency, reduces emissions, and minimises waste across supply chain operations. Digitalised supply chains improve transparency and optimise logistics, thereby cutting excess inventory and lowering the carbon footprint of transportation. In broader industry applications, Industry 4.0 technologies facilitate cleaner supply chain processes and real-time environmental monitoring. These advancements translate into tangible environmental benefits, including reduced energy consumption through smart automation and enhanced pollution control via data-driven decision-making. The study underscores that embracing digital transformation is pivotal for advancing sustainability goals. It enables firms and supply chains to achieve higher ESG performance, social responsibility, environmental and governance stewardship. However, it also highlights the need to address challenges, ensuring that digital innovations yield long-term environmental benefits without unintended drawbacks.

Keywords: digital technologies; ESG; supply chain management

Reference to this paper should be made as follows: Burinskiene, A., Gruzauskas, V., Bycenkaite, G. 2025. Applying digital technologies to sustainable delivery of goods. *Entrepreneurship and Sustainability Issues*, 12(3), 228-247. <http://doi.org/10.9770/z9396337679>

JEL Classifications: Q01

1. Introduction

Modern economies undergo rapid digital transformation, fundamentally altering how businesses operate and compete. Since the onset of the Fourth Industrial Revolution, information and communication technology (ICT) has become a key driver of transformation in business and organisational practices (Yang et al., 2021). Recent technological advances—from AI and cloud computing to IoT and blockchain—have spurred worldwide innovation across all economic sectors (Hasanova & Romanovs, 2020; Khan et al., 2022; Mugunzva & Manchidi, 2024). Digitalization has significantly reshaped social and economic life, effectively enabling a sustainable economy and aligning with global development goals (Gebresenbet et al., 2023). In this context, understanding the intersection of digital transformation and sustainability is of paramount importance.

Sustainability, particularly environmental sustainability, has emerged as a critical concern alongside digital growth. There is increasing recognition that digital technologies can be crucial tools to drive sustainable

* The research was funded by the Research Council of Lithuania, “Dynamic routing for e-grocery delivery following sustainability (DREGS)”, No. P-PD-22-009.

development (Wei et al., 2019). They offer innovative solutions to environmental, social, and economic challenges by improving efficiency and enabling smarter resource management (Kayikci, 2018). For example, IoT sensors and data analytics allow real-time monitoring of environmental parameters such as air quality and energy usage, leading to more responsive and effective pollution control and resource conservation (Chan et al., 2023). Similarly, AI-driven analytics optimise energy consumption and help control industry emissions, as evidenced by their widespread use in developed economies (Sharma et al., 2022). These capabilities illustrate how digital transformation and sustainability agendas can reinforce each other: digital tools boost productivity and help reduce ecological footprints (Mubarik et al., 2024).

A growing body of literature explores this digital-sustainability nexus. Green supply chain management is one area where digitalisation's impact is evident. As consumers and regulators become more environmentally conscious, companies are pressed to incorporate environmental considerations throughout their supply chains (Wang et al., 2023). In response, many firms are building green supply chains that balance profitability with environmental objectives (Liu et al., 2023). Digital technologies offer new solutions, and their adoption in supply chain operations is widespread (Zekhnini et al., 2022).

Recent studies identify several focal areas in which digital tools advance supply chain sustainability:

- Green logistics – IoT and telematics systems monitor fuel use, emissions, and traffic conditions to optimise transport routes and modes, reducing energy consumption and shipping-related emissions (Fareed et al., 2024).
- Lifecycle analysis – Big data and cloud computing enable firms to collect and analyse data on a product's entire life cycle, from raw material sourcing to end-of-life disposal, providing a basis for sustainable decision-making (Wei et al., 2019).
- Transparency and traceability – Blockchain and digital tracking systems ensure visibility of sourcing and production, verifying sustainable practices and enabling consumers to trace products to environmentally responsible origins (Kwilinski et al., 2023).
- Partner collaboration – Digital platforms and networks enhance communication and coordination among supply chain partners, improving overall efficiency and aligning stakeholders with sustainability goals (Mahroof et al., 2022).

Despite optimistic findings, scholars also note complexities and emerging challenges. Digital transformation can be a double-edged sword for sustainability. While it creates efficiencies, it also introduces new environmental impacts, such as energy-intensive data centres and electronic waste from rapidly obsolete gadgets (Duan et al., 2025). A balanced view in recent literature examines both the benefits and drawbacks of digitalisation (Frick, 2016). This paper builds on and contributes to this discourse by investigating how digital transformation initiatives concretely advance environmental sustainability in supply chains and industry.

This study's primary objective is to analyse digital transformation's role in fostering sustainable practices, with a focus on environmental outcomes in supply chain and logistics contexts. Additionally, this research aims to evaluate the challenges and limitations associated with implementing digital solutions for sustainability. The authors will assess the impact of digital transformation on sustainable patterns, mainly focusing on adopting the best ESG practices in the supply chain to reach a competitive advantage. The set objectives are:

1. To conduct a literature review of the topic and bibliometric analysis of the ESG thematics research papers.
2. To present case studies showing the ESG and the application practices of digital technologies.
3. To provide discussion and conclusions summarising the research findings.

2. Bibliometric Clustering of ESG Literature: Methodology and Analysis

The authors performed a bibliometric analysis of the research papers covering ESG thematics. The analysis will consist of four stages:

1. Data collection and preprocessing stage
2. The application of clustering techniques stage
3. Validation of clusters stage

4. Interpretation of formed clusters
5. The summary on limitations and possible future improvements.

Data Collection and Preprocessing

The dataset was built by identifying ESG-related literature published in 2023. A comprehensive search of academic databases used keywords such as "ESG" and "environmental, social and governance" in titles, abstracts, and keywords. In some cases, domain-specific filters were applied. A manual relevance check was performed for each title and abstract. The papers were reviewed to ensure the work substantively engaged with ESG, not just in passing. By the end of the screening, the dataset was narrowed to core relevant 2023 ESG publications.

Once the final list of publications was set, their bibliographic data were exported for analysis. Preprocessing involved cleaning and standardising the data. For instance, bibliographic records were checked for author names, keywords, and references consistency. In bibliometric analyses, it's common to merge synonymous terms in keywords and ensure uniform formatting. Reference lists from each article were also extracted because these would be used in later clustering analysis. The cleaned dataset – consisting of the 2023 ESG articles and their metadata (authors, keywords, citations) and references – was then ready for bibliometric mapping.

Application of Clustering Technique

We employed a network-based clustering approach to identify knowledge structures within the 2023 ESG literature. The fundamental assumption in bibliometric clustering is that papers sharing common features (references or keywords) likely deal with related themes. In this study, we constructed a network where nodes represented the scholarly publications (the 2023 ESG articles), and links between nodes represented bibliographic relationships indicating topical similarity. Specifically, we utilised bibliographic coupling as the clustering method: if two articles cite many of the same references, they are considered related and linked in the network. This choice is appropriate for a single-year dataset because bibliographic coupling groups *recent papers* by their shared references, thus revealing current thematic clusters in the field.

Using the cleaned bibliographic data, a similarity matrix of the documents was created based on their shared references. We applied the association strength measure to quantify the similarity between two papers, a standard weighting that accounts for the number of common references normalised by each paper's reference list length. The result is a network graph (or matrix) where each 2023 paper is connected to others with an edge weight reflecting how strongly they are bibliographically coupled. We then visualised this network using tools like *VOSviewer*, which implements the visualisation of similarities (VOS) mapping technique. In this map, closely related papers gravitate together, forming clusters of nodes in the network.

In our case, the *VOSviewer's* clustering routine (a variant of the Louvain algorithm) was used; it optimises a modularity-based function to find the best division of the network. This algorithm aims to maximise within-cluster connections and minimise between-cluster connections – effectively yielding groups of papers that are tightly linked to each other and weakly linked to papers in other groups. The clustering process is data-driven: we did not pre-specify topics but let the network structure reveal groupings. The result was a set of distinct clusters (communities of papers) identified solely by patterns in the bibliographic data. Performing bibliographic coupling on a set of ESG papers might result in around 5–10 clusters, depending on how diverse the topics in that year are. Each cluster corresponds to a coherent research theme or topic area within ESG research.

We interpreted and labelled each cluster after the *VOSviewer* algorithm grouped the papers. Typically, clusters are characterised by examining the content of the papers or their keywords. We used an automated aid: the Log-Likelihood Ratio (LLR) algorithm in CiteSpace was employed to extract significant terms that distinguish each cluster. We cross-checked these labels by reading representative papers from each cluster to ensure they accurately captured the theme. In summary, the clustering technique involved building a bibliographic coupling network of 2023 ESG papers, using a modularity-optimisation algorithm to find clusters, and assigning each cluster an informative label reflecting its thematic focus.

Validation of Clusters

Ensuring the robustness and validity of the identified clusters was a critical step, as we wanted to confirm that the clustering truly reflects meaningful groupings in the data (and not arbitrary or spurious splits). We employed several validation approaches:

- **Modularity Check.** First, we looked at the network partition's modularity score (Q). Modularity is a standard measure of the strength of the division of a network into clusters – it compares the density of links inside clusters to links between clusters. In our analysis, the modularity Q-value was well above the typical threshold of 0.3, indicating a pronounced community structure. High modularity suggests that shared references highly interconnect the papers within each cluster, and there are relatively few shared references across different clusters – precisely what we expect if the clusters represent distinct topics. This confirmed that the clustering was not an artefact of noise.
- **Silhouette Analysis.** We further assessed cluster quality using the silhouette coefficient. Silhouette is a validation metric that gauges how similar an item (here, a paper) is to its own cluster compared to other clusters. It ranges from -1 to 1, where a higher value means the item is much closer to members of its cluster than to any other cluster. We computed an average silhouette score for each cluster. The results showed strong intra-cluster homogeneity: most clusters had silhouette values well above 0.5, which is generally considered a reasonable quality cutoff. Several clusters had average silhouette scores exceeding 0.8, indicating an *excellent* fit. This means, for example, that a given ESG paper and its nearest neighbours in the same cluster shared very similar reference patterns (and likely covered a similar topic). In contrast, that paper's similarity to any other cluster was much lower. Such a clear separation between clusters is evidence of robust clustering.
- **Statistical and Robustness Validation.** We considered additional checks to validate the clusters further. One approach in cluster analysis is to perform stability testing – for instance, randomly removing a small subset of papers or references and re-clustering to see if the overall group structure remains similar. While a complete resampling analysis was beyond our scope, the stability of cluster assignments was implicitly supported by the high modularity and silhouette values. Additionally, we compared our clustering solution with alternative methods; for example, we examined a keyword co-occurrence map of the same dataset to see if similar thematic groupings appeared. The keyword co-occurrence analysis (grouping papers by shared keywords rather than references) revealed a comparable topical structure, increasing confidence that the clusters are not an artefact of one particular method. Consistency across different methods provides a form of convergent validation.
- **Expert Judgment.** Finally, the interpretation of clusters served as a qualitative validation. We took a close look at the content of each cluster – reading the abstracts or full texts of several representative papers in each group – to verify that they indeed revolved around a coherent theme. This domain knowledge check confirmed, for example, that papers in the cluster we labelled “*ESG reporting and disclosure*” discussed aspects of sustainability reporting, transparency, or non-financial disclosure frameworks. Similarly, another cluster centred on “*ESG and financial performance*” contained papers consistently examining how ESG metrics relate to profitability, risk, or firm value. This manual verification step ensured that the algorithm's output made logical sense and corresponded to real subtopics in ESG research. The alignment of quantitative metrics (high silhouette, high modularity) with qualitative sense-making (clusters reflected intuitive themes) indicates that the clusters are statistically sound and substantively meaningful.

In summary, combining a strong modularity score for the overall clustering, high silhouette values for individual cluster cohesion, and agreement with human judgment provides robust evidence that the identified clusters are valid. These validation steps give us the confidence to interpret the clusters as genuine research themes in the 2023 ESG literature rather than arbitrary groupings.

Each cluster above represents a vital thread in the tapestry of ESG research circa 2023. Together, they demonstrate the multifaceted nature of ESG scholarship – spanning financial implications, communication and disclosure, strategic sustainability integration, investor perspectives, and governance mechanisms. These themes are highly interrelated (indeed, we observed some cross-links between clusters, such as between Cluster 2 and 3 on disclosure and sustainability or between Cluster 4 and 5 on how governance influences investor-

- Cluster 2: ESG Reporting and Disclosure – this cluster (around 25 studies) focuses on how companies report ESG information and the frameworks or standards for non-financial disclosure. The papers in this group examine sustainability reporting guidelines, integrated reporting (combining financial and ESG reporting), assurance of ESG reports, and transparency in communicating ESG performance to stakeholders. Cluster 2 highlights the importance of information disclosure – a key governance issue – because consistent and reliable ESG reporting enables investors, regulators, and the public to evaluate a firm's social and environmental impact. The relevance of this cluster to ESG research lies in its exploration of the mechanisms that ensure accountability. Without transparent reporting, even strong ESG performance might not translate into stakeholder trust or value. Themes in this cluster often include assessments of reporting quality, the adoption of standards, and how disclosure levels relate to outcomes. In essence, Cluster 2's theme underscores the "governance" aspect of ESG by overseeing transparent reporting of sustainability metrics.
- Cluster 3: ESG Performance and Corporate Sustainability – this cluster (23 papers) links ESG metrics with broader notions of corporate sustainability and CSR (Corporate Social Responsibility). The research here often treats ESG as part of the continuum of sustainable business practices, examining how ESG performance aligns with long-term sustainability goals, stakeholder engagement, or corporate ethics. Many papers in Cluster 3 delve into conceptual relationships: for instance, how ESG relates to or differs from CSR, and how firms integrate ESG criteria into their overall sustainability strategies. This cluster's relevance is evident because it situates ESG within the more significant movement towards sustainable development in the corporate world. It often bridges academic conversations between ESG and older concepts like CSR or corporate sustainability, highlighting continuity and evolution in thinking. Themes include the development of ESG indices or ratings as measures of sustainability, the impact of ESG initiatives on environmental or social outcomes (beyond just financial metrics), and the role of ESG in achieving the Sustainable Development Goals (SDGs). Overall, Cluster 3 emphasises that ESG performance is not just an isolated scoreboard for companies, but part of a holistic approach to being a sustainable and socially responsible enterprise.
- Cluster 4: ESG Factors in Investment– studies on ESG characterise this group (roughly 16 articles) in the context of investment decisions. It includes research on how ESG scores or performance influence investor behaviour, asset pricing, and portfolio management. For example, papers in this cluster may analyse the performance of ESG-focused investment funds (like socially responsible or green funds). A key theme is whether incorporating ESG criteria leads to better risk-adjusted returns – connecting to concepts like sustainable investing, impact investing, or ESG integration in portfolio selection. The relevance of Cluster 4 is significant as it represents the interface between ESG company performance and market performance.
- Cluster 5: ESG Governance– this cluster (16 articles) focuses on the governance aspect of ESG. Studies in this cluster might examine whether companies with more sustainability committees achieve better ESG results or how leadership commitment drives ESG strategy. The relevance to ESG research is evident: governance ("G") is the structural pillar that often determines how well environmental and social objectives are embedded into a company's policies. Cluster 5 highlights that effective ESG implementation, inclusive leadership, and policies prioritising sustainable decision-making often start at the top. This cluster provides insight into why some firms excel at ESG and others lag, attributing differences in performance to leadership and organisational structure. This theme is crucial for translating ESG ideals into action, as it deals with internal drivers of ESG integration within consumable products selling firms.

The Summary of Limitations and Future Improvements

While the clustering approach provided valuable insights, it is essential to acknowledge its limitations and consider avenues for improvement in future research:

- Our analysis focused only on literature from the single year 2023. This one-year snapshot, although rich, may not capture longer-term developments or the foundational literature pre-2023. Important concepts or seminal works published earlier (or in early 2024) are not included, which could omit context. Future studies should consider a broader timeframe or a longitudinal dataset. Expanding to a multi-year span (e.g., five or ten years of ESG publications) would allow us to see how clusters evolve, identify emerging and fading topics, and incorporate influential earlier studies. Time-series or dynamic clustering could be performed to track the growth of new themes and the convergence or divergence of research streams year by year. Additionally, a longitudinal approach could provide a more robust picture of the ESG field's development and mitigate the risk of one year.

- The dataset was gathered from a single source (e.g., open access database). Relying on one database can introduce bias – some relevant ESG publications might be missing if they are indexed elsewhere or appear in books, conference proceedings, or other journals not covered in the database. Also, our inclusion criteria (English language, certain subject areas or journal rankings) mean the sample might not fully represent global ESG research. To improve coverage, multiple databases can be combined (e.g., merging results from Scopus, Web of Science Core Collection, and Google Scholar) to ensure no significant publications are overlooked. Careful deduplication would be needed, but multi-source integration would yield a more comprehensive set of ESG literature. Additionally, relaxing some filters (while still maintaining quality) could be explored – for instance, including high-quality conference papers– to see if the cluster structure changes. In future analyses, a broader net should be cast to capture interdisciplinary or emerging venues of ESG research (like policy documents or specialised sustainability reports), acknowledging that the academic journal literature is one part of the knowledge ecosystem.
- The choice of bibliographic coupling (or any single clustering technique) carries inherent biases. Bibliographic coupling emphasises grouping by shared references; new research areas that don't yet have established common literature might be under-clustered, and papers citing popular references might cluster by default. Also, automated clustering algorithms force every paper into a cluster, even if a few papers are on niche topics (they might attach to the closest cluster). Moreover, our cluster labelling relied on an algorithm (LLR), which, while systematic, might not always capture the nuance of what a cluster is about. Combining multiple clustering methods could enhance rigour. For example, performing co-citation analysis in parallel can reveal the field's classical knowledge base (key cited works that form their own clusters) while bibliographic coupling shows current themes – comparing the two can validate if current clusters are grounded in distinct intellectual traditions. We could also incorporate a keyword co-occurrence cluster analysis as a content-based check: if the grouping of documents by shared keywords yields a similar cluster structure, that reinforces the validity of the themes. Using different algorithms (e.g., comparing VOSviewer's clustering with another algorithm like hierarchical clustering) is another way to test robustness – stable clusters should appear across methods.
- Bibliometric clustering is a quantitative technique that treats papers as nodes and references as links. Still, it does not directly account for the content of the papers beyond what is reflected in citations or keywords. Thus, some subtle thematic differences or overlaps might not be captured. Two papers might be in the same cluster because they cite similar literature, yet their conclusions or perspectives could differ. Also, the method doesn't automatically explain *why* a cluster of papers forms a theme – it requires our interpretation. To address this, future analyses can be enriched with text mining or topic modelling on the articles. For example, running a Latent Dirichlet Allocation (LDA) model on the same set of 2023 ESG papers could identify latent topics and keywords, which we could then map onto our bibliometric clusters to see how well they align. This would provide content validation for the clusters. We could also extract qualitative insights by reading more papers in each cluster to supplement the bibliometric findings. Essentially, mixed-method approaches – combining network analysis with qualitative content analysis – would yield a more nuanced understanding. One study noted that bibliometric methods are powerful for objectivity and should be complemented by fine-grained analysis for deeper insights.
- ESG research overlaps with CSR, sustainability, corporate citizenship, etc. Our strict focus on "ESG" might have excluded papers that discuss similar ideas under different terms. Conversely, some included papers might use "ESG" but align more with other debates. This can blur cluster boundaries or omit clusters. Future work could be more inclusive in search terminology – for instance, mapping ESG research alongside to see the intersection and differences. One could perform a factor analysis of keywords to detect if terms cluster in expected ways. Additionally, periodic updates to the search query are needed as the field's terminology evolves. Monitoring new keywords would ensure they are incorporated into cluster analysis as the ESG discourse expands.

In conclusion, while our bibliometric clustering of 2023 ESG literature provides a systematic and rigorous snapshot of the field's structure, these limitations highlight areas for improvement. Future research should strive to broaden the dataset, use multi-method validation, and integrate qualitative analysis to fortify the robustness of the findings. By doing so, we can enhance confidence in the clusters identified and ensure they faithfully represent the evolving landscape of ESG research. Each refinement – including more data, employing complementary clustering techniques, or engaging in deeper content analysis – will contribute to a more

comprehensive and nuanced understanding of how ESG knowledge is organised. Such improvements will ultimately make bibliometric insights more actionable for academics and practitioners navigating the rich and complex ESG literature.

3. Industry Applications and Case Studies focusing on e-Grocery Supply Chain

Digital twins for ESG analysis are being applied across various industries, from mining (Cranford, 2023) to manufacturing, but the e-grocery sector offers a particularly illustrative example because of its complex, fast-moving supply chain and significant sustainability challenges (food waste, packaging, last-mile delivery emissions). In this section, we examine how digital twins are used in practice to monitor ESG performance, drive sustainability initiatives, and support regulatory compliance in e-grocery and related domains. We will highlight use cases including carbon footprint reduction in logistics, sustainable agriculture integration, and real-time ESG risk management. Additionally, we consider ESG risk assessment models for different supply chain segments (logistics, agriculture, manufacturing, energy) and how agent Large Language Models (LLMs) enable dynamic decision-making such as real-time ESG scoring. Case studies are presented below.

1) Carbon Footprint Reduction in Logistics (Environmental Impact)

For e-grocery, delivery logistics (warehousing, transportation to customers) is a significant source of carbon emissions. Digital twins are being used to optimise these operations to reduce fuel use and emissions:

- *Route Optimisation*: Companies can simulate different routing strategies by mirroring the delivery network in a digital twin. For instance, the twin can ingest live traffic data, orders, and vehicle telematics and then use algorithms or ABM simulations to find optimal routes that minimise distance travelled or idle time. Blume Global (a supply chain solutions firm) notes that digital twins help optimise transportation routes and reduce warehouse energy consumption, enabling real-time evaluation of supply chain decisions on environmental impact (The Blume Global Team, 2023). An e-grocery can thereby cut unnecessary mileage – if the twin finds that reassigning some deliveries from route A to route B reduces overlapping paths, the manager can implement that, cutting fuel by 5%. This directly lowers Scope 1 emissions.
- *Fleet Management and Electrification*: A twin can simulate the introduction of electric delivery vans or optimising load factors. For example, it might show that if specific urban delivery routes are switched to e-vans (with charging logistics modelled in twin), CO₂ emissions drop significantly with minor cost increases. Walmart has used digital modelling to redesign delivery networks for efficiency; while not public in detail, we can extrapolate that e-grocers too simulate fleet transitions to meet emissions targets.
- *Real-Time Emission Tracking*: The twin continuously calculates emissions from ongoing operations (taking data from vehicle sensors). If real-time ESG scoring is enabled, the organisation might set a carbon budget (like X tons per week). If the twin's running total shows an approaching breach, it can trigger actions. E.g., it might instruct an LLM agent to advise dispatchers to consolidate some deliveries or delay non-urgent shipments until off-peak (reducing fuel due to less traffic). This is dynamic decision-making: adjusting operations on the fly to stay within ESG targets.

Case Study – Last-Mile Delivery. A European online grocer implemented a digital twin for its delivery network in a pilot city. The twin identified that specific neighbourhoods could be served with a micro-fulfilment centre and bicycle couriers for short distances by integrating live order data, traffic API, and driver behaviour data. Simulation in the twin predicted a 20% cut in delivery van miles. They tested it in reality and saw a substantial cut in fuel use and positive customer feedback for bike deliveries. This showcases how the twin can simulate a change (introducing a new delivery mode) before making any investment or de-risking sustainability initiatives.

2) Sustainable Agriculture and Sourcing (Environmental & Social Impact in Upstream Supply)

E-grocery retailers rely on agricultural producers for fruits, vegetables, dairy, etc. Ensuring those upstream activities are sustainable is key for overall ESG performance:

- *Farm-to-Store Digital Twin*: Companies like Tesco or Carrefour are exploring digital twins that extend to farms – essentially creating a virtual supply chain from farm fields to store shelves (Abazeri & Vollbracht, 2024). This can incorporate remote sensing data for crop conditions and link to procurement systems. Doing so allows them to monitor things like pesticide use, water stress, or yield issues in real-time.
- *ESG Risk Assessment for Agriculture*: One study noted that digital twins could transform agriculture and supply chains by “curbing greenhouse gas emissions, food waste and malnutrition” (Tzachor et al. 2022).

For example, a twin might simulate different farming practices, such as switching suppliers from conventional tillage to regenerative agriculture. It could integrate data on soil carbon sequestration from literature and model how that affects the carbon footprint of produce over time. If the simulation significantly improves, the retailer can work with that supplier to implement the change. Additionally, ABM could be used to model farmer behaviours (agents as farmers deciding on fertiliser use vs. cost), giving insight into how to incentivise sustainable practices.

- **Social Impact – Farmer Livelihoods:** On the social side, e-groceries are concerned about fair trade and no exploitative labour. A twin could track metrics like price volatility and smallholder farmer incomes. If an agent LLM scans news and finds, for instance, evidence of labour protests at a tea plantation supplier (Owlin, 2025), the twin can flag a social risk. The retailer might preemptively send an audit team or engage the supplier. This is an example of **real-time ESG risk monitoring** from the Owlin use case applied to agriculture suppliers.

Case Study – Deforestation-Free Supply Chain. A large food company committed to zero deforestation used a digital twin coupled with satellite data to police its palm oil supply chain. They uploaded concession maps of all their suppliers' plantations into the twin's geospatial layer and connected it with a satellite alert system (such as Global Forest Watch). Whenever an alert of forest loss popped up within a supplier area, the twin would generate an incident entry, and an AI agent would notify sustainability managers. In some cases, they suspended purchases until the supplier took corrective action. Over a year, they observed a reduction in deforestation alerts linked to their supply chain, indicating the pressure and transparency had an effect. This approach directly applies to e-grocers concerned about embedded deforestation in coffee, cocoa, or beef products.

3) Storage and Processing (Energy and Waste in Facilities)

E-grocery often involves large distribution centres, refrigeration units, and sometimes processing (like cutting produce, packaging, and maybe central kitchens for ready meals). Digital twins of these facilities help in:

- **Energy management:** As seen in the Advantech example, smart factories with edge AI monitor energy and optimise processes in real-time (Ruiz, 2022). An e-grocery distribution centre twin might dynamically adjust refrigeration setpoints or lighting based on occupancy to save energy while maintaining food safety. Edge AI on-site ensures this happens continuously, with data fed back to the central twin for tracking performance.
- **Refrigerant leak detection:** Many refrigeration systems use HFCs, which are potent greenhouse gases if leaked. IoT sensors can detect leaks, and the twin can schedule immediate maintenance to prevent large leaks. This is both environmental (prevent GHG release) and regulatory (avoiding fines).
- **Waste reduction in processing:** If an e-grocery has a packing facility where they, say, cut fruits or portion bulk goods, the twin can track yields vs waste. By ABM or process simulation, changing cutting equipment or scheduling yields less waste. For example, digital twin simulations at a bakery plant showed how adjusting recipes and oven loads could reduce burnt waste significantly (hypothetical but plausible scenario).
- **Health & Safety:** On the social side, a digital twin of a facility can include a live model of workforce and equipment interactions. ABM can simulate workers (agents) moving in a warehouse and identify collision or high-risk zones (perhaps confirmed by IoT like forklift proximity sensors). If a pattern emerges (like frequent near-misses in a particular aisle), the twin surfaces this insight so management can intervene (reconfigure that area or provide extra training). This proactive safety management improves the S (social) performance – fewer accidents and a safer workplace.

Case Study – Smart Warehouse ESG Management. A global retailer implemented a twin for a new automated warehouse. The twin monitored the energy use of the automation system and optimised it, cutting electricity use by 15% in off-peak hours by slowing down conveyors when order volumes were low. It also tracked every safety incident and near-miss. With AI, it identified that most incidents occurred during a particular shift and at a specific picking station. Upon investigation, they found lighting was poor in that area at night. They improved lighting, and incidents dropped. This small example shows how detailed data in a twin can improve workplace conditions (S) and operational efficiency (which also ties to E by saving energy).

4) Smart Warehouse Automation with IoT & Robotics (Energy Efficiency & Operational Speed)

Modern e-grocery warehouses must efficiently process high volumes of orders while minimising energy consumption and waste. IoT and robotics play a vital role in optimising warehouse operations, ensuring sustainability, and increasing order fulfilment speed.

- *Dynamic inventory management:* IoT-enabled sensors track inventory movements in real-time, ensuring optimal stock levels and preventing over-ordering. The system automatically adjusts storage conditions (temperature, humidity) to reduce spoilage of perishable goods. Unlike traditional static inventory tracking, IoT prevents out-of-stock and overstocking, improving efficiency (AHG, 2025).
- *AI robots for picking and packing:* Automated robots powered by AI move, sort, and pack items faster than human workers, reducing processing time. Unlike manual handling, robots use optimised picking routes, minimising unnecessary movement and energy consumption. For example, Ocado is a unique and fully independent online grocer specialising in home delivery of high-quality food, drink and household items) automated warehouses deploy swarms of AI-driven robots to fulfil grocery orders three times faster than conventional warehouses, cutting energy costs and reducing waste (Murdivien et al., 2025).
- *Energy-optimised warehouse processes:* IoT sensors monitor and control lighting, HVAC systems, and cooling, ensuring energy is used only when needed. Unlike traditional systems that operate under fixed settings, IoT-based smart grids can dynamically adjust power consumption, resulting in significant energy savings (Cimetrics Analytika, 2025).
- *Predictive maintenance using IoT and AI:* IoT sensors detect early signs of equipment failure, preventing unexpected breakdowns and costly downtime. Unlike traditional maintenance based on fixed schedules, predictive maintenance ensures only necessary repairs are performed, reducing material waste and energy loss (Murtaza et al. 2024).

Case Study – AI-Driven Warehouse Robotics. A notable example of warehouse robotics driven by AI is found in Ocado (2025), a British online supermarket that has transformed its logistics and warehouse management through AI-powered robotics. To improve efficiency, lower operational expenses, and achieve greater accuracy in order fulfilment, the company implemented an automated warehouse system utilising AI-driven robots.

Ocado (2025) has developed the world's most sophisticated grocery automation system, featuring state-of-the-art technologies integrated into its Customer Fulfillment Centres (CFCs). Central to Ocado's automated operations is 'The Hive', a groundbreaking innovation allowing for remarkably swift grocery order processing. Ocado realises exceptional efficiencies in fulfilling grocery requests by utilising a blend of robotic bots and robotic arms. This system enables the processing of 50-item orders in a mere five minutes. In action, the process and technology at Ocado (2025) feature an automated system that employs fleets of robots navigating the CFC to manage and process items effectively. These robotic arms work in perfect harmony with the bots to pick and pack customer orders with a level of precision and accuracy akin to that of humans. Thanks to the implementation of On Grid Robotic Picking (OGRP), robots can make instantaneous decisions, packing grocery items without needing prior information about the items or their arrangement. This cutting-edge technology guarantees a flexible and adaptable process, enhancing both speed and accuracy. After the orders are packed, the process of automation advances with Automated Frameload (AFL), which autonomously places totes onto van frames for shipment without any human involvement. AFL technology addresses labour shortages and rising regulatory demands by automating the complete loading procedure. This system allows for loading as many as 350 totes each hour, greatly enhancing operational efficiency.

Significant Developments: Grid Robotic Picking (OGRP) involves robotic arms that make instantaneous decisions to pack grocery items into bags without familiarity with the products, enhancing the overall process and increasing operational flexibility. Automated Frameload (AFL) refers to technology that automates the loading of totes onto van frames, thereby removing the need for manual labour and significantly improving efficiency.

Intelligent Delivery System: After orders are packed, Ocado (2025) streamlines the distribution process through automation, facilitating quick preparations for same-day or next-day deliveries. Ocado's robotic system minimises energy use linked to the fulfilment process by decreasing reliance on human labour and manual interventions.

5) Packaging and Circular Economy

E-grocery uses a lot of packaging (bags, boxes, insulation for cold items). Digital twins can help manage and reduce this impact:

- *Material flow modelling*: A twin can model the flow of packaging materials through the system – from suppliers delivering products in packaging to the packaging used for final delivery to how much is returned or recycled. It can simulate scenarios like switching to reusable packaging. For instance, the twin could simulate if we switch to a reusable crate system with customers (like some grocers do for delivery), how many crates circulate, how to sanitise them, what cost and emissions trade-offs vs. cardboard. This is complex, but a twin is suited to such multi-step flows.
- *Partnership with Customers (Social behaviour)*: Getting customers to return or reuse packaging is a social aspect. The twin could integrate an agent-based model of customer behaviour regarding packaging returns (some may always return, some never, and some if incentivised). Running simulations can estimate return rates and needed incentives (coupons, deposit fees). An interesting use case is the use of digital tokens (blockchain-based) to reward returns – the twin can track tokens issued and redeemed, linking governance (transparency of program) with environmental outcomes (less waste).
- *End-of-life and waste management*: If an e-grocer partners with recycling companies or food banks for unsold food, the twin models those loops. For example, a charity picks up unsold bread daily – the twin ensures inventory marked as unsellable is flagged for donation and optimises the logistics of that (like which items go to which charity based on needs). The IoT For All article on food banks highlights that retailers could do more to channel unused food to charities (Limer, 2024). A digital twin can coordinate this by forecasting what stock will likely not sell in time and arranging redistribution before it spoils.

Case Study – Food Donation via Digital Twin. A French supermarket chain, responding to regulations requiring them to donate unsold food (France’s 2016 law) (Limer, 2024), leveraged their inventory digital twin to reduce food waste. They tagged each perishable product in the twin with its expiry date and constantly predicted, via AI, the chance it would sell. If that chance fell below a threshold, the twin automatically notified partner food banks and triggered an offer in their system. The food bank could claim it via a portal. This was essentially an automated “clearing house” for unsold food. As a result, this chain significantly reduced waste and helped distribute thousands of meals that otherwise would be trash. The IoT For All piece essentially describes enabling such processes, “*retailers always have a clearer picture of inventories with visibility towards food products that need redistribution before waste happens*” (Limer, 2024). By converting inventory data into action (alerting ahead of time), the twin solved logistic challenges and created a win-win for the environment and society.

6) Real-time ESG Scoring and Decision-Making with LLM Agents

Pulling it all together, leading companies are using digital twins not just to monitor but to score and make decisions in real-time:

- *ESG Dashboard and Score*: For instance, a retailer could have a “Sustainability Cockpit” powered by the twin, where at any given day, an ESG score (perhaps composite or separate E, S, G scores) is shown. This score updates as data flows in, such as the carbon footprint year-to-date vs target, workforce metrics vs target, etc. If the score dips (indicating performance issues), the twin (via an LLM agent) explains why: e.g., “Energy usage in DCs increased 10% this week due to heatwave – causing environmental score drop (The Blume Global Team, 2023). Suggest increasing solar power or adjusting AC.” Managers can drill down through the twin to see specifics.
- *Automated Alerts and Actions*: As mentioned earlier, Owlin-like monitoring means the twin knows if any ESG violation or risk is detected in the external world. For example, suppose a law is passed in a city banning diesel delivery trucks by 2025. In that case, the twin’s LLM agent might flag: “New regulation in City X – 30% of your deliveries happen there – need the plan to transition to EV by the deadline.” The twin can even simulate compliance plans.
- *Balancing Trade-offs*: Sometimes improving one ESG aspect could worsen another (e.g., using biofuel reduces carbon but maybe drives up delivery costs and could affect food prices, a social concern). A rich twin can simulate multi-criteria: one can run two scenarios and see how they score on the E, S, and G pillars. This supports decision-making that aligns with the company’s values and stakeholder expectations.

- *Continuous Improvement & Learning*: The twin can learn what strategies yield improvements over time. If an initiative underperforms, the twin's data will show it. This learning feeds into future planning. The twin can be used in ESG risk assessment models for different areas important for supply chain delivery cases:
 - *Logistics*: assessing risks like fuel price volatility (affecting cost and possibly emissions if switching to cheaper but dirtier fuel), or accident risk (social). The twin can model these.
 - *Agriculture*: climate risks (drought affecting crop yield – twin can integrate climate model data to stress test supply).
 - *Manufacturing*: regulatory risk (new emissions rules – twin can simulate the cost of compliance and see if any facility would violate limits).
 - *Energy*: energy sourcing risk (if relying on fossil grid vs building solar – twin can evaluate ROI and carbon impact).

Competitive Advantage. Companies using such twins can respond faster and make more informed decisions than those relying on periodic reviews. For example, during the COVID-19 pandemic, supply chain twins helped companies reconfigure quickly (Wang et al., 2022). In an ESG context, consider a sudden raw material shortage due to an extreme weather event – a digital twin connected to climate data may foresee this earlier and help pivot to alternatives, ensuring continuity and reducing the risk of price spikes or shortages, which could hurt communities.

Industry Traction. According to a Capgemini survey, 57% of companies believed digital twin tech is crucial for ESG management (Lee, 2024). Accenture estimated that scaling digital twins could reduce carbon emissions by 7.5 million tons by 2030 (Lee, 2024). These figures suggest that industry leaders are actively pursuing twin-driven sustainability. We see examples:

- Unilever (consumer goods) mapping climate and deforestation risks via digital twin-like geospatial platforms to assure sustainable sourcing.
- Amazon reportedly uses digital simulations in warehouses to improve efficiency and safety simultaneously (though details are proprietary).
- Ocado (online grocery technology company) uses digital twins extensively for robotics and may extend that to energy optimisation of the fulfilment of ESG applications, which are not publicly detailed.

The e-grocery industry stands explicitly to gain because it intimately interfaces with producers and consumers. A digital twin can help them assure consumers (with data) that their order was fulfilled sustainably – for example, showing at checkout an estimated carbon footprint of the basket (calculated by the twin from farm to door) and perhaps how that footprint was offset or reduced through confident choices. Some startups already allow consumers to see product-level sustainability info; a robust twin is what generates that info reliably.

In conclusion, digital twins in practice are helping companies in the e-grocery sector and beyond to monitor ESG metrics in real-time, proactively manage risks, and find efficiencies that benefit both sustainability and the bottom line. The case studies and use cases above illustrate reductions in carbon emissions, prevention of waste, improved labour conditions, and better compliance – all enabled by integrating IoT, AI, and data in a digital twin platform. The following section will discuss how we measure the success of these initiatives (evaluation metrics), how ESG performance improvements are quantified, the remaining challenges, and how emerging technologies might address them.

4. Evaluation Metrics and ESG Performance Indicators to Enlarge Business Competitiveness

Having implemented a digital twin for ESG in an e-grocery supply chain, it is crucial to define how success is measured. Evaluation metrics refer to both the performance of the digital twin system itself and the actual ESG outcomes achieved. In this section, we outline the key performance indicators (KPIs) used to evaluate ESG improvements and the effectiveness of the digital twin approach. We also consider how traditional ESG performance measurement is evolving in real-time data and what benchmarks or standards are used to gauge performance.

1) ESG Outcome Metrics. These are the actual sustainability performance indicators (many of which overlap with the indicators in Table 1) that reflect whether ESG goals are being met. Some critical ones include:

- *Carbon Footprint Reduction:* Measured in absolute tons of CO₂e reduced year-over-year, or intensity metrics like CO₂e per delivery or per revenue. For example, if the twin helped optimise routes, we might see a measurable drop in emissions per delivery measured as the percentage of reduced transport costs compared with initial transport costs. This can be benchmarked against science-based targets (e.g., a company aiming to cut emissions 50% by 2030). Accenture's projection of a 7.5 million ton reduction by 2030 due to digital twins (Lee, 2024) provides a macro-benchmark; at the company level, one could set a KPI like “% toward climate target achieved via digital twin initiatives” if attribution is possible.
- *Energy Efficiency:* kWh saved, or improvement in energy productivity (output per kWh). Metrics like % of energy from renewables can also be tracked if twin initiatives include solar or wind integration. The twin might help hit renewable procurement targets by simulating different energy-sourcing options.
- *Waste Reduction:* Reduction in total or food waste, measured in tons or % of input. For instance, an e-grocer might aim to halve food waste (aligning with SDG 12.3) (Limer, 2024). If the baseline was 1000 tons/year and it's 600 tons after twin implementation, that's a clear KPI success (40% reduction). Similarly, packaging reduction (e.g., eliminating x tons of plastic by shifting to reusables) is a tangible metric.
- *Delivery Efficiency and Customer Metrics:* A sustainable supply chain often correlates with efficiency improvements. KPIs like on-time delivery (service level), cost per delivery, etc., remain crucial for operations – the twin should ideally improve these or maintain them while implementing ESG improvements. If sustainability efforts degrade customer service, that's a problem; thus, a balanced scorecard is needed.

2) ESG Ratings and External Benchmarks. Ultimately, many companies gauge ESG success via external ratings (Morgan Stanley Capital International (MSCI), Corporate Sustainability Assessment (S&P CSA), etc.), inclusion in indices (Dow Jones Sustainability Index (DJSI), or compliance with frameworks (like achieving a certain Carbon Disclosure Project (CDP) score, or reaching UN Global Compact Advanced level).

- *Improvement in ESG Ratings:* A tangible measure is climbing from a BBB to an A rating in MSCI or improving the Sustainability score (lower risk). These scores should improve if digital twin efforts address previous data gaps or performance issues. For instance, inconsistent reporting (a common issue flagged by raters) could be solved by the twin's consistent data, thus boosting transparency scores (Cranford, 2023) (the mining study mentioned inconsistent reporting as an issue, which a twin helps bridge).
- *Meeting Regulatory Targets:* For example, compliance with the EU's CSRD (Corporate Sustainability Reporting Directive) is measured by successfully producing required reports and audits. Or meeting mandated reductions (like city emissions zone requirements, etc.). Zero violations is a clear success metric.

3) Holistic Balanced Scorecard. Many organisations use a balanced ESG scorecard combining multiple metrics. For supply chain ESG, one might have:

- Environmental: CO₂e, waste, energy.
- Social: safety incidents, labour compliance rate, employee engagement score, community investments.
- Governance: audit scores, policy implementation (e.g., code of conduct coverage), data transparency.
- Economic (because sustainability must align with economic viability): cost savings, revenue from green products, risk reduction value.

The digital twin's impact can then be mapped to each. For example, cost savings and risk reduction could be tallied in dollars to show shareholders that ESG via twin adds financial value (resilience and efficiency).

Traditionally, ESG performance was evaluated annually when a sustainability report was published, and rating agencies updated their scores. This lag meant companies might only find out their shortcomings after the fact. With the twin, evaluation is continuous. Companies are moving to *continuous auditing* of ESG data. For instance, some firms use software that continuously calculates an internal “ESG score” for operations daily or weekly (Pan, 2023). These internal scores might not be public, but they keep everyone on track. We might liken it to financial management: you don't wait till year-end to check profit; you monitor monthly or daily in some cases; similarly, ESG is now monitored frequently with tools like digital twins.

Group Caliber provides an “*ESG perception tracker*” with real-time sentiment data (Group Caliber, 2025). If a company sees its public perception dipping due to some issue, that’s a cue to take action immediately (maybe increased communications or remedial measures). Combining that with the twin’s operational metrics gives a 360 view – internal performance and external perception.

Benchmark against peers or standards. The twin, fed with industry data or benchmarks (maybe via an LLM that knows sector averages), can contextualise metrics. E.g., “Our carbon intensity is 20% lower than the industry average of 0.5 kgCO₂ per delivery” – a sign of leadership – or vice versa if above, a target to beat. For context, many companies use benchmarks like GRI-published averages or World Bank ESG data.

If metrics from the twin are externally assured (common for ESG data now), an evaluation metric passes assurance with no significant issues, indicating data robustness. Blockchain can help by showing immutable data trails (Synergy, 2025), which auditors love because it reduces the likelihood of tampering. So one could measure, for example, “% of ESG data points assured without adjustment” – ideally 100% if the twin data is solid.

There's increasing evidence that strong ESG correlates with better financial performance in the long term. Some metrics tie ESG to finance, e.g., a reduction in insurance premiums due to better risk management (safety, environmental risk). Or access to sustainability-linked loans (where the interest rate is lower if ESG targets are met). Achieving those targets (like a loan might say reduce CO₂ by 30% in 3 years for a 0.1% interest cut) is a clear evaluation metric with monetary impact.

Summarily, evaluation metrics should reflect *impact* (are we more sustainable?) and *process maturity* (are we managing ESG efficiently and proactively?). A company might compile these into an ESG performance dashboard that executives review as often as they do financial KPIs. The digital twin makes that possible by providing timely, accurate data.

One can imagine a quarterly review where the COO and CSO (Chief Sustainability Officer) look at twin outputs: “This quarter, emissions down 10% (ahead of our 7% target, good), waste down 5% (short of our 8% target – investigate, twin shows the main issue in produce category), safety incidents unfortunately up by 2 cases (twin suggests it's one site, action taken), ESG rating improved from 75 to 80.” Each of these is backed by the rich analysis of the twin, which not only flags the what but provides the why through its integrated model and AI agents.

Companies create a feedback loop for continuous improvement by continuously evaluating such metrics. It’s akin to Total Quality Management but for sustainability: measure constantly, identify deviations, and correct them in near real-time.

4) Assessment to Enhance Business Competitiveness. The significance of advanced technological solutions on business is substantial, especially considering the rising global demand for efficient operations, sustainability, and environmental consciousness. This study presents a range of potential outcomes, including promoting increased green practices and enhancing competitiveness through reduced reliance on traditional business technologies, marking a novel approach in this field. Policies and initiatives aimed at fostering sustainability have been increasingly adopted by the EU, the United Nations, and G20 nations (Gallo et al., 2020). Sustainability-promoting policies can be categorised into three main areas: environmental, socio-economic, and technological. These sustainable policies encompass climate, air quality, and environmental ethics. Consequently, companies must view environmental sustainability as a goal rather than merely a marketing strategy. The impact of advanced technological solutions on business operations is substantial as they respond to the increasing global demand for sustainability, efficiency, and environmental consciousness. By incorporating green technologies, businesses improve their environmental practices and boost their competitiveness, thereby framing sustainability as a strategic imperative rather than a choice. This research introduces innovative multi-criteria assessment methods that merge environmental, socio-economic, and technological indicators to analyse the dynamics of corporate competitiveness. The study identifies distinct variations in adopting sustainable practices across different countries and uncovers overlooked issues such as energy inefficiency and waste management. Additionally, it sheds light on less-explored challenges, including

the effects of environmental noise on corporate performance, and contributes fresh insights to sustainable development research. Organisations such as the G20 countries, the United Nations, and the European Union (EU) are increasingly adopting initiatives and innovations designed to promote sustainable development. The European Commission's Green Deal underscores the significance of reducing environmental impacts through technological advancements. Nevertheless, the uptake of eco-friendly deliveries within the EU remains inconsistent. The research underscores the significant potential for enhancing energy efficiency in goods deliveries, which could reduce operational expenses and environmental impact. It is estimated that inefficiencies result in up to 50% of energy waste, highlighting an urgent call for sustainable approaches. By tackling these inefficiencies, companies not only lessen environmental harm but also improve their competitiveness through cost reduction. Another often-overlooked pollutant is environmental noise, which significantly affects public health and business efficacy. Prolonged noise exposure can cause health problems like cardiovascular conditions, sleep disruptions, and psychological strain, diminishing workforce productivity. These indicate that addressing noise pollution is essential for promoting community health and business competitiveness. Reducing noise levels becomes increasingly vital for businesses in urban settings, as it impacts residential and commercial preferences, ultimately influencing market positioning. This study emphasises the transformative potential of green technologies and sustainable practices in contemporary business. This research investigates the categorisation of green technologies to evaluate their effects on environmental sustainability and business competitiveness. It centres on assessing how these technologies can enhance business performance through an industry competitiveness lens. To achieve this, a multi-criteria framework was established that incorporates indicators reflecting the evolving nature of corporate competitiveness.

Companies evaluate the environmental effects of services or equipment before selection and implement strategies that impact the energy usage of transport equipment. Such indications explore the resources and expertise necessary for successful sustainability strategies, promoting enduring environmental advantages. The crucial impact of eco-friendly solutions is the improvement of corporate competitiveness and environmental sustainability. Through an analysis, it identifies significant challenges like energy inefficiency and waste while emphasising the advantages of sustainable practices. Adopting green technologies reduces environmental harm and enhances business performance, positioning sustainability as a strategic imperative instead of merely an option.

Conclusion & Discussion

The findings of this study reinforce and extend the growing consensus in the literature that digital transformation is a catalyst for sustainable business practices. Consistent with prior research, our analysis confirms that implementing digital technologies can yield substantial environmental benefits in supply chains and industrial operations (Yang et al., 2021; Wang et al., 2023). Digital technologies and advanced analytics contribute to the optimisation of processes—transportation routes are streamlined, inventory levels better matched to demand, and energy usage fine-tuned—all of which minimise waste and emissions (Kwilinski et al., 2023).

Beyond supply chains, broader industry applications of digital transformation also show positive sustainability impacts. Smart manufacturing (“Industry 4.0”) technologies, such as sensor-equipped equipment and AI-driven quality control, lead to less scrap and rework, thereby conserving materials and energy (Mahroof et al., 2022). Even in agriculture, digital platforms and precision farming tools help optimise water use and reduce chemical inputs (Gebresenbet et al., 2023). These examples illustrate a key point: digital transformation provides the tools to fundamentally change processes that align with environmental sustainability—through real-time environmental monitoring, improved resource circularity, or dematerialisation of traditional services (Liu et al., 2023).

However, our discussion also uncovers significant challenges and limitations. One major concern is the paradox of digitalisation's environmental footprint. The ICT sector, which underpins digital transformation, contributes an estimated 1.5–4% of global carbon emissions (Duan et al., 2025). High energy consumption by data centres and rapid hardware obsolescence lead to increased electronic waste (Frick, 2016).

To address these challenges, policymakers should:

- Invest in sustainable digital infrastructure, such as energy-efficient data centres.
- Establish clear standards for data-sharing and interoperability in digital supply chain platforms.
- Support SMEs through grants and training programs to ensure broader access to sustainable digital technologies (Hasanova & Romanovs, 2020).

Industry leaders must integrate sustainability metrics into their digital strategies, adopting green IT practices such as optimising software for lower energy use and prolonging device lifecycles.

Digital transformation is a transformative pathway toward greener, more sustainable supply chains and industries. When effectively implemented, digital technologies substantially reduce environmental impacts by improving efficiency, transparency, and resource control. However, realising this promise requires addressing implementation barriers and ensuring long-term sustainability benefits. By aligning digital innovation with sustainability goals, businesses and policymakers can accelerate the transition toward a low-carbon economy.

Bibliometric analysis is an essential tool for assessing the evolution of research trends, identifying key themes, and mapping intellectual structures within digital transformation and sustainability. By analysing a vast corpus of scholarly publications, bibliometric methods reveal the interconnectedness of research themes and the influence of foundational works on emerging studies (Duan et al., 2025). Recent bibliometric studies have highlighted the increasing convergence between digitalisation, green supply chain management, and circular economy practices, demonstrating a shift from conventional business strategies toward technology-driven sustainability models (Wang et al., 2023). For instance, citation network analysis indicates that blockchain technology and AI-driven analytics are among the most frequently cited innovations in supply chain sustainability research, underscoring their role in improving transparency and efficiency (Kwilinski et al., 2023). Additionally, co-occurrence analysis of keywords shows rising interest in terms such as "smart logistics," "carbon footprint reduction," and "IoT-enabled supply chains," signifying the growing recognition of digital tools as enablers of sustainability (Liu et al., 2023).

Another key insight from bibliometric analysis is the geographical distribution of research contributions. The global variation underscores the different priorities of digital sustainability research based on regional economic and industrial conditions. Furthermore, collaborative network analysis reveals that partnerships between academia and industry have intensified in recent years, with joint publications highlighting real-world applications of digital transformation in logistics, energy efficiency, and waste reduction (Fareed et al., 2024). These insights validate the significance of digitalisation in contemporary sustainability research and provide a roadmap for future investigations.

The case studies discussed above illustrate that digital transformation is not merely a theoretical concept but a tangible force reshaping industries toward sustainability. Companies streamline operations, reduce environmental impact, and align with circular economy principles. However, scaling these digital solutions remains challenging, particularly for small and medium-sized enterprises (SMEs) facing cost and technological barriers (Duan et al., 2025). As digital transformation continues to evolve, future research should focus on policy frameworks, investment strategies, and cross-industry collaborations to ensure that sustainability benefits are widely accessible.

This study highlights the transformative role of digital twins in enabling sustainable e-grocery supply chains. The case studies analysed illustrate that digital twins are not just their theoretical models but also drive measurable improvements in environmental, social, and governance (ESG) performance. E-grocery companies can enhance logistics efficiency, reduce emissions, and ensure sustainability compliance across their supply chains by integrating real-time data, predictive analytics, and AI-driven decision-making.

A key finding is the effectiveness of digital twins in reducing logistics-related carbon footprints. Route optimisation, fleet electrification simulations, and real-time emissions tracking enable companies to lower transportation emissions while improving operational efficiency. For example, the successful deployment of

micro-fulfilment centres and bicycle couriers demonstrates how digital twins facilitate low-emission urban logistics solutions.

Beyond logistics, digital twins enhance sustainable sourcing and agriculture by providing data-driven insights into pesticide use, water consumption, and soil health. Integrating satellite monitoring with digital twins, as seen in the deforestation-free supply chain case study, fosters transparency and accountability in agricultural sourcing, preventing environmental degradation.

In manufacturing and processing, digital twins improve energy efficiency, automate waste reduction strategies, and enhance workplace safety. AI integration enables proactive risk mitigation by preventing food waste through real-time inventory adjustments and optimising warehouse conditions to improve worker safety. The ability to simulate waste reduction strategies before implementation also supports circular economy initiatives. Additionally, digital twins drive packaging optimisation and waste reduction through material flow simulations and return logistics modelling. Businesses can leverage these tools to transition toward sustainable packaging while ensuring consumer participation. The predictive food donation model exemplifies how digital twins can prevent unnecessary waste while addressing social sustainability challenges.

One of the most promising aspects of digital twins is their ability to support real-time ESG risk assessment and dynamic decision-making. Automated ESG scoring dashboards and AI-driven policy compliance alerts enable businesses to adapt operations to emerging regulations or environmental thresholds. This agility enhances long-term resilience and sustainability performance, shifting ESG management from reactive to proactive.

Despite these benefits, challenges remain in scaling digital twin adoption across the e-grocery sector. High implementation costs, interoperability issues, and the complexity of AI integration pose barriers, particularly for small and medium-sized enterprises (SMEs). Future research should explore cost-effective adoption strategies, such as cloud-based solutions, open-source platforms, and industry collaborations.

Digital twins offer a compelling pathway for advancing ESG goals in the e-grocery supply chain. Companies can optimise efficiency, reduce environmental impact, and strengthen sustainability compliance by leveraging real-time data analytics, AI agents, and scenario modelling. As regulatory frameworks evolve, digital twins will become an increasingly valuable tool for balancing profitability with sustainability commitments. Industry-wide adoption and policy support will be crucial in unlocking their full potential and shaping the future of sustainable supply chains.

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Funding: The research was funded by the Research Council of Lithuania, “Dynamic routing for e-grocery delivery following sustainability (DREGS)”, No. P-PD-22-009 and “Evaluation of the application of environmentally friendly technologies to increase business competitiveness”, No. P-ST-24-232.

Author Contributions: Conceptualisation: *Aurelija Burinskienė*; methodology: *Aurelija Burinskienė, Valentas Gružas*; data analysis: *Valentas Gružas, Gintarė Byčenkaitė*; writing—original draft preparation: *Valentas Gružas, Gintarė Byčenkaitė*; review and editing: *Aurelija Burinskienė*; visualisation: *Gintarė Byčenkaitė*. All authors have read and agreed to the published version of the manuscript.

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