



POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Measuring the Environmental Impact of e-Grocery Distribution Networks

MASTER OF SCIENCE IN FOOD ENGINEERING

SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

Author: Janitha Chandimal Abeyrathna Siriwardhana

Student ID: 249027

Advisor: Professor Angela Tumino

Co-advisor: Giulia Galli

Academic Year: 2023-24

Abstract

This work includes an extensive systematic literature review aimed at examining the current state of the E-grocery distribution network using the reviewed papers. The literature review covers e-grocery, environmental impact, and logistics, which constitute the originality elements of this work. This study specifically investigates the methods used to measure the environmental impacts as well as the environmental impacts of e-grocery systems, focusing on the distribution chain, operational practices, and technological strategies that influence emissions and energy demand. The systematic review findings were categorized into four key aspects: logistics infrastructure, transport operations, product-specific logistics, and operational and technological strategies. Life Cycle Assessment (LCA), particularly using the ReCiPe framework, is the most common method for quantifying impacts across distribution systems. Results revealed centralized systems achieve economies of scale but are highly sensitive to routing efficiency and vehicle technology; decentralized systems reduce travel distances yet may cause high aggregate emissions during peak demand. Hybrid networks offer flexibility but require consideration of embedded impacts from vehicle production and infrastructure. At the last mile, parcel lockers and crowdsourced delivery showed strong potential for emission reduction, whereas click-and-collect exhibited mixed results depending on customer travel behavior. Additional findings highlight packaging and cold chain logistics as major contributors to ecological burdens. Reusable, lightweight, and recycled packaging materials benefit when supported by circular systems. Fleet composition strongly influenced sustainability, with electric vehicles, cargo bikes, and drones outperforming conventional fleets, though trade-offs such as material demand and regulatory challenges remain. The integration of logistics infrastructure, transport operations, product-specific logistics, and operational and technological strategies is essential to designing greener, more efficient distribution systems that align with future sustainability goals.

Keywords – E-grocery, Last-mile, Logistics, Environmental Impact

Abstract (Italian)

Questo lavoro include un'ampia revisione sistematica della letteratura volta ad esaminare lo stato attuale della rete di distribuzione dei prodotti alimentari online utilizzando gli articoli esaminati. La revisione della letteratura copre i prodotti alimentari online, l'impatto ambientale e la logistica, che costituiscono gli elementi di originalità di questo lavoro. Questo studio indaga in modo specifico le metodologie di misurazione delle emissioni e di altri impatti dei sistemi di vendita online dei prodotti alimentari, studiando allo stesso tempo i risultati dell'applicazione delle metodologie e quindi l'impatto ambientale delle vendite, concentrandosi sulla catena di distribuzione, sulle pratiche operative e sulle strategie tecnologiche che influenzano le emissioni e la domanda di energia. I risultati della revisione sistematica sono stati classificati in quattro aspetti chiave: infrastrutture logistiche, operazioni di trasporto, logistica specifica dei prodotti e strategie operative e tecnologiche. La valutazione del ciclo di vita (LCA), in particolare utilizzando il framework ReCiPe, è il metodo più comune per quantificare gli impatti nei sistemi di distribuzione. I risultati hanno rivelato che i sistemi centralizzati consentono di ottenere economie di scala, ma sono molto sensibili all'efficienza dei percorsi e alla tecnologia dei veicoli; i sistemi decentralizzati riducono le distanze di viaggio, ma possono causare emissioni aggregate elevate durante i picchi di domanda. Le reti ibride offrono flessibilità, ma richiedono di tenere conto degli impatti incorporati derivanti dalla produzione dei veicoli e dalle infrastrutture. Nell'ultimo miglio, gli parcel lockers e la consegna in crowdsourcing hanno mostrato un forte potenziale di riduzione delle emissioni, mentre il click-and-collect ha mostrato risultati contrastanti a seconda del comportamento di viaggio dei clienti. Ulteriori risultati evidenziano che l'imballaggio e la logistica della catena del freddo sono i principali responsabili dell'impatto ecologico. I materiali di imballaggio riutilizzabili, leggeri e riciclati traggono vantaggio dal supporto dei sistemi circolari. La composizione della flotta ha influito notevolmente sulla sostenibilità, con i veicoli elettrici, le cargo bike e i droni che hanno superato le flotte convenzionali, anche se permangono compromessi quali la domanda di materiali e le sfide normative. L'integrazione delle infrastrutture logistiche, delle operazioni di trasporto, della logistica specifica dei prodotti e delle strategie operative e tecnologiche è essenziale per progettare sistemi di distribuzione più ecologici ed efficienti, in linea con i futuri obiettivi di sostenibilità.

Parole chiave - E-grocery, Ultimo miglio, Logistica, Impatto ambientale

Table of Contents

Abstract.....	i
Abstract (Italian).....	ii
Table of Contents	iii
List of tables	v
List of Figures	vi
Acknowledgement.....	vii
1. Introduction	1
1.1. Research Background	1
1.2. Rationale of the Research.....	4
1.3. Objective and Research Question	7
1.4. Expected Outcome of the Research	8
2. Methodology.....	9
2.1. Conceptual Framework of the Research.....	9
2.2. Scope Definition	10
2.3. Identifying and Selecting Relevant Studies	11
2.4. Data Analysis.....	14
3. Results.....	17
3.1. Logistic Infrastructure	18
3.1.1. Environmental Impact Metrics and Assessment Methods in Network Structure	18
3.1.2. Environmental Impact Metrics and Assessment Methods in Last Mile Infrastructure	19
3.1.3. Environmental Impact Metrics and Assessment Methods Based on Packaging	24
3.2. Transport Operations	25
3.2.1. Environmental Impact Metrics and Assessment Methods Based on Vehicle 25	
3.2.2. Environmental Impact Metrics Based on Delivery Time	28
3.3. Product Specific Logistics	28
3.3.1. Environmental Impact Metrics and Assessment Methods in Cold Chain Logistics	28
3.4. Operational and Technological Strategies.....	29

3.4.1.	Optimization Approach.....	29
4.	Discussion	31
4.1.	Logistic Infrastructure	32
4.1.1.	Environmental Impact Metrics and Assessment Methods in Network Structure	32
4.1.2.	Environmental Impact Metrics and Assessment Methods in Last Mile Infrastructure	38
4.1.3.	Environmental Impact Metrics Based on Packaging	42
4.2.	Transport Operations	44
4.2.1.	Environmental Impact Metrics and Assessment Methods Based on Vehicle 44	
4.2.2.	Environmental Impact Metrics based on Delivery Time	47
4.3.	Product Specific Logistics	48
4.3.1.	Environmental Impact Metrics and Assessment Methods in Cold Chain Logistics	48
4.4.	Operational and Technological Strategies.....	49
4.4.1.	Optimization Approach.....	49
5.	Conclusion	51
	References	54

List of tables

Table 1: Keywords for the Selected Three Elements.....	11
--	----

List of Figures

Figure 2.1: Conceptual Framework of the Research	11
Figure 2.3: PRISMA chart summarizing the systematic review of the literature, with details on the search strings and inclusion and exclusion criteria.....	16

Acknowledgement

I would like to express my sincere gratitude to Professor Angela Tumino, my supervisor, for giving me the invaluable opportunity to work under her guidance and I am also deeply thankful to Giulia Galli, PhD student at Politecnico di Milano, for her continuous assistance, thoughtful advice, and constructive suggestions throughout this work. Her support and collaboration have been greatly appreciated.

I would also like to extend my heartfelt appreciation to my family and friends for their unwavering support, patience, and motivation, which have been essential in helping me complete this academic journey.

Finally, I acknowledge the use of artificial intelligence (AI) tools, including ChatGPT by OpenAI and Grammarly, to assist in improving the clarity, grammar, and structure of some sections of this thesis.

1. Introduction

1.1. Research Background

In recent years, Electronic commerce (E-commerce) has experienced rapid global growth, with retail E-commerce sales rising from 4,248 billion USD in 2020 to 5,311 billion USD in 2022 (Kundu et al., 2025). In 2023, 20.8% of the total retail market was dominated by E-commerce (Dayal et al., 2025), a trend further accelerated by the COVID-19 pandemic. This also led to the digital revolution in the retail industry, with even grocery stores that heavily rely on brick-and-mortar stores increasingly adopting digital technologies. This acted as a precursor for E-grocery, and according to EU data, the proportion of citizens engaging in online shopping deliberately increased from 60% in 2017 to 73% in 2021. Mainly in Italy, the number of consumers purchasing groceries online increased from 18% before the pandemic to 30% during it (Clement & Spinler, 2025). E-commerce is a dynamic, multifaceted field reshaping commerce worldwide and can be defined as the buying and selling of goods and services, including the transfer of funds or data, over an electronic network, primarily the internet. It encompasses various models, such as business-to-consumer (B2C), business-to-business (B2B), and consumer-to-consumer (C2C) transactions, enabling companies and individuals to conduct commerce online (A.A. & A., 2022).

The food and grocery sector, commonly referred to as E-grocery, has witnessed a 15% growth in 2022, making it one of the most dynamic product categories under the E-commerce umbrella (Adolph, 2016). While paving the way for significant shifts in contemporary retail practices, E-grocery has established a strong presence and rapidly expanded, not only revolutionizing supply chain and distribution systems but also changing consumer behavior (Ghazal et al., 2025). Therefore, this accelerating growth emphasizes the significance of E-grocery and the need for a clear understanding of its scope and definition.

E-grocery can be defined as the process of purchasing groceries online through digital platforms and having them delivered to your doorstep or collected at designated pickup points or retail establishments (Leloup et al., 2024). This is also considered a form of Quick-commerce (q-commerce), which can be regarded as 'a fast form of an on-demand delivery that delivers products ordered online to customers in less than an hour' (Huang & Yen, 2021), underscoring the significance of the delivery time. The recent exponential growth in internet access and mobile phone use, along with consumers' familiarity with digital marketplaces, has opened numerous avenues for retail sellers to boost their sales (Nguyen et al., 2018), thereby making a substantial contribution to E-grocery. This is supported by changes in consumer behavior, which are strongly connected to transport (Suel & Polak, 2017). Compared to traditional brick-and-mortar retail, consumers greatly benefited from this approach by its time saving, enhanced convenience, and round-the-clock access to a wide range of products. Furthermore, this framework demonstrates significant potential for tackling challenging logistical requirements that traditional delivery services, such as postal and standard courier systems, often fall short of meeting. These include maintaining temperature conditions for different kinds of products, adhering to strict delivery time windows (Arevalo-Ascanio et al., 2025), integrating with inventory to ensure stock availability to synchronize order fulfillment (Winkelmann et al., 2024), real-time order tracking, which enables customer communication (Cagliano et al., 2017), etc.

From an environmental sustainability perspective, E-grocery presents both potential challenges and implications. Multiple studies suggest that E-grocery may be more environmentally sustainable than conventional brick-and-mortar shopping, with emissions reductions ranging from 10% to 30% in context. This is largely attributable to the grouped deliveries and a reduction in individual car journeys to retail outlets (Siragusa & Tumino, 2022). Moreover, centralized order fulfillment centers, along with automated picking systems, have demonstrated lower energy consumption and emissions, as well as lower pre-order resource and waste generation (Wu et al., 2024).

Micro-fulfillment centers (MFCs) with highly automated systems can minimize double handling and optimize inventory, thereby reducing spoilage and energy waste by 16-54% (Kemp et al., 2022). Consumers are paying heightened attention to sustainable packaging in E-grocery as well. Research suggests that the industry is facing requirements for novel sustainable packaging materials, such as those from cellulose and others that enable package reuse and extended material lifecycles in reverse logistics (Lai et al., 2022). Despite these benefits, the E-grocery sector faces considerable operational challenges.

Due to additional complexity, many companies struggle to succeed in E-grocery, particularly in order preparation. Here, order fill rate is of utmost importance, which refers to the percentage of customer orders that are immediately filled by available stocks (Larsen, C., & Thorstenson, 2008). Some studies indicate that E-grocery ventures can be compromised by failure to meet customer orders at the point of purchase (de Magalhães, 2021). These inefficiencies affect the environmental outcomes, as unfulfilled or partially fulfilled orders often lead to additional trips, increased delivery distances, and higher energy consumption. Therefore, when evaluating environmental measurement techniques in E-grocery distribution, it is crucial to account for such operational aspects, as they significantly contribute to carbon emissions and overall sustainability performance. Moreover, last-mile delivery, where the goods are delivered from the local distribution center to the customer, is also a great concern due to its significant effects on operational cost (Shuaibu et al., 2025). In addition, the environmental and economic effects of deliveries and returns using vans in cities have led to several problems in terms of ecological sustainability (Galkin et al., 2025). These include noise pollution, traffic congestion, higher accident risks, infrastructure degradation, and prolonged travel times (Amaya et al., 2025). Air pollution due to high CO₂ emissions resulting from delivery vehicles in the E-grocery framework has also been shown to cause several deleterious effects. CO₂ is considered the key greenhouse gas (GHG) that significantly

contributes to global warming as well as associated climate change. Among many others, logistics is one of the biggest contributors of CO₂ emissions to the environment (Ponce et al., 2024). Even though online shopping has the potential to reduce carbon emissions associated with personal shopping trips between households and physical retail stores, the growth of E-grocery may also lead to an increase in carbon emissions through excessive use of packaging and, most notably, through delivery transportation (Tudisco et al., 2025). Therefore, by analyzing the aforementioned, an understanding can be obtained regarding the environmental sustainability of the E-grocery logistics.

E-grocery operations are also closely linked to the efficiency and sustainability of last-mile logistics. The last-mile logistics, which refer to the final stage of a business-to-consumer (B2C) delivery process, connect the order penetration point, typically a fulfillment center, to the consignee's designated delivery location, such as a residence or a designated collection point (Zhang et al., 2025). Unlike general E-commerce, the last-mile in E-grocery faces unique challenges, including the need for strict cold-chain maintenance for perishables, short delivery time windows to preserve freshness, and the high frequency of small, fragmented orders. These constraints often require more vehicles, shorter routes, and multiple delivery attempts, significantly influencing fuel consumption, emissions, and overall environmental performance (Galkin et al., 2025) (Boysen et al., 2021). This study focuses on all three stages of the distribution network and provides a comprehensive analysis.

1.2. Rationale of the Research

As mentioned in the previous section, over the past few decades, the E-commerce sector has seen robust growth, supported by the exponential rise in internet and smartphone penetration. While these platforms provide consumers with exceptional satisfaction, a wide range of choices, and a personalized shopping experience, they have also introduced logistical challenges, particularly in handling perishable goods

that require stringent temperature control, faster delivery, and enhanced inventory coordination, thereby increasing logistical complexity. Additionally, last-mile delivery is one of the most demanding segments of the E-grocery supply chain. This includes several concepts; home delivery remains the most common method, offering direct shipment to consumers, and it often leads to missed deliveries, multiple delivery attempts, and product returns, which result in longer travel distances (Galkin et al., 2025)(Ram et al., 2024). This trend is contributing to the rise of air and noise pollution, as well as greater traffic congestion in densely populated regions (Galkin et al., 2025). Click-and-collect is another last-mile delivery method that allows customers to pick up orders from physical stores, reducing transportation distance. Moreover, parcel lockers and smart lockers provide contactless 24/7 access, enabling minimized failed deliveries (Ram et al., 2024)(Maxner et al., 2024). Temperature-controllable smart lockers have also been introduced for grocery items that require cold chain maintenance and are in increasing demand in the E-grocery sector. One such example is the Refrigerated Smart Locker by AirLocker, which is quite similar to a fridge and is used for grocery delivery in E-grocery (Luis et al., 2022). Pickup points or third-party collection locations further enhance delivery efficiency. Other than that, emerging technologies such as drone delivery, autonomous vehicles, and robots offer promising solutions to reduce labor costs and emissions (Ram et al., 2024). Therefore, in a world where approximately 73% of global carbon emissions are attributed to the energy sector, with transportation being a major contributor, efficient last-mile delivery systems should be aimed for, not only to lower distribution costs and enhance customer satisfaction, but also to minimize carbon emissions (Agoo et al., 2025).

The growth in the E-grocery sector has introduced unique challenges to the field of logistics, particularly in the transport of temperature sensitive goods. These include fresh produce, dairy, meat, frozen foods, and pharmaceuticals, in which freshness and integrity should be maintained due to their highly perishable nature. Compared to conventional trading, E-grocery operations often involve fragmented delivery routes

and shorter delivery windows, which make temperature and quality control challenging (Tsang et al., 2024). As consumer demand for convenience and fresh goods continues to grow, the efficiency, reliability, and sustainability of cold chain systems have become critical factors in ensuring customer satisfaction and loyalty.

Zhao et al. (2023) provided a concise definition of cold chain logistics for agricultural commodities. Accordingly, it is a specialized transportation system that employs refrigeration and temperature control technologies to maintain the freshness and integrity of agricultural products throughout all stages of the supply chain, from storage and packaging to transportation and final distribution (Zhao et al., 2023). Currently, rapid growth in demand for cold chain logistics is being observed globally. In the first eight months of 2023, China, the world's largest grocery market, generated a total revenue of \$43.3 billion by handling 240 million tons of temperature sensitive goods. It is estimated that this market will reach \$121.9 billion by 2025, with new E-commerce transactions expected to reach \$90.8 billion by 2027 (Tsang et al., 2024). However, the problem lies in the fact that cold chain delivery is a complex process involving safety, efficiency, intelligence, and cooperation, notwithstanding its significant contribution to global carbon emissions (Shi et al., 2022).

Considering all the above-mentioned details, it is understandable that, given the significant ecological impact of E-grocery distribution systems, it is essential to adopt a quantitative approach to address these concerns regarding the environmental sustainability of E-grocery logistics. As noted above, recent research has highlighted the need for comprehensive analyses of the environmental impacts of e-grocery services, particularly focusing on energy consumption and CO₂ emissions. Such reviews synthesize existing studies, identify research gaps, and provide a foundation for developing strategies to mitigate the environmental impact of e-grocery services. Therefore, this study seeks to evaluate the environmental impacts of E-grocery logistics and identify existing research gaps. The findings are intended to inform and

support future academic research and practical initiatives to minimize the environmental footprint of E-grocery operations.

1.3. Objective and Research Question

As mentioned in the previous sections, consumers have greatly benefited from improved convenience and accessibility to a wide range of products around the clock, driven by recent advancements in E-grocery, which have opened new avenues for retail logistics. Despite its merits, this approach has also introduced new logistical complexities, especially in ecological aspects of the last mile of the delivery process (Toniolo et al., 2025). While prior studies have explored operational challenges and consumer behavior in E-grocery (Leloup et al., 2024), the quantitative assessment of the environmental impact of these logistics networks across the distribution channel remains limited. As indicated above, the current body of knowledge largely focuses on last-mile delivery innovations such as home delivery, parcel lockers, and autonomous vehicles (Ram et al., 2024), with a growing body of research analyzing carbon emissions associated with urban delivery systems (Amaya et al., 2025). However, it was observed that most of these studies give consideration to either traditional E-commerce or individual sections of the delivery chain, and lack a comprehensive, sustainability focused evaluation of all three logistics stages in an E-grocery framework.

Additionally, although some studies suggest that order bundling and centralized fulfillment can reduce emissions (Wu et al., 2024), the environmental costs of delivery transportation, particularly CO₂ emissions, remain underexplored in empirical models that cover the entire supply chain. As emphasized by Kemp et al. (2022), there is a need for a critical assessment of even cutting-edge technologies, such as micro fulfillment centers, on their actual ecological impact across varying logistics operations.

Thus, the author observed a void in the literature for integrative, evidence-based studies examining the environmental footprint of last-mile logistics in E-grocery. Addressing this gap is essential to guide the design of sustainable delivery networks that not only meet consumer demands but also contribute to a healthy environment. Therefore, this study aims to provide a quantitative evaluation of the environmental impacts associated with E-grocery logistics systems, with specific attention to the last-mile delivery stages. This is expected to lead to the identification of critical sustainability pressure points, which will support the generation of evidence-based insights for the development of more environmentally efficient strategies in E-grocery distribution.

Therefore, by considering the aforementioned, the author pursues the objective of ‘to critically and comprehensively evaluate the environmental impacts associated with the E-grocery distribution networks across different delivery stages, namely the last-mile, and to determine appropriate methodologies for their assessment within the context of sustainable E-grocery logistics’.

Thus, to achieve the stated objective, the study seeks to answer the research questions of: ‘RQ1: Which established methodologies can be used to assess these impacts in the context of e-grocery logistics? RQ2: What are the environmental impacts of e-grocery distribution networks across different categories?’

1.4. Expected Outcome of the Research

The expected outcome of this research is to provide a clear, data driven understanding of the environmental impacts linked to E-grocery distribution networks. By identifying key pressure points and existing gaps in current practices, the study aims to guide future improvements in sustainable logistics. Ultimately, the findings are anticipated to support the development of more eco-efficient strategies within the E-grocery sector.

2. Methodology

2.1. Conceptual Framework of the Research

Initially, a comprehensive and systematic analysis of the extant literature on the environmental impacts of the E-grocery distribution network was conducted to evaluate current findings and identify gaps in this research area. To review in a well structured and meticulous manner, a systematic literature review (SLR) methodology proposed by Denyer & Tranfield (2009) was selected by the author. Denyer and Tranfield's approach is widely accepted in management science and operations literature, making it an academically sound choice for a thesis that lies at the intersection of supply chain, environmental science, and e-commerce. In addition, this review methodology was found to be consistent with the study's focus on sustainability, logistics, and operations management, and was therefore selected. This methodology provides a clear framework for the literature review, initially including defining the research scope and formulating a focused research question, which is crucial in a broad and emerging research area like this. The review methodology further includes locating relevant studies, which ensures transparency and reproducibility. This is particularly important in establishing reliability in analyzing a diverse range of studies that involve varying environmental metrics and methodologies. Moreover, adopting this framework paves the way for the development of a structured database of environmental impacts, which also facilitates comparative analysis across different E-grocery delivery models. This is crucial for identifying gaps in current practices. The final stage focuses on synthesizing data and generating actionable recommendations.

This aligns with the thesis's objective, which is not just to understand environmental impacts but to offer insights into more sustainable logistics models in the E-grocery sector. Thus, this review methodology is an ideal fit for conducting the literature review.

The following figure illustrates this adopted SLR methodology.

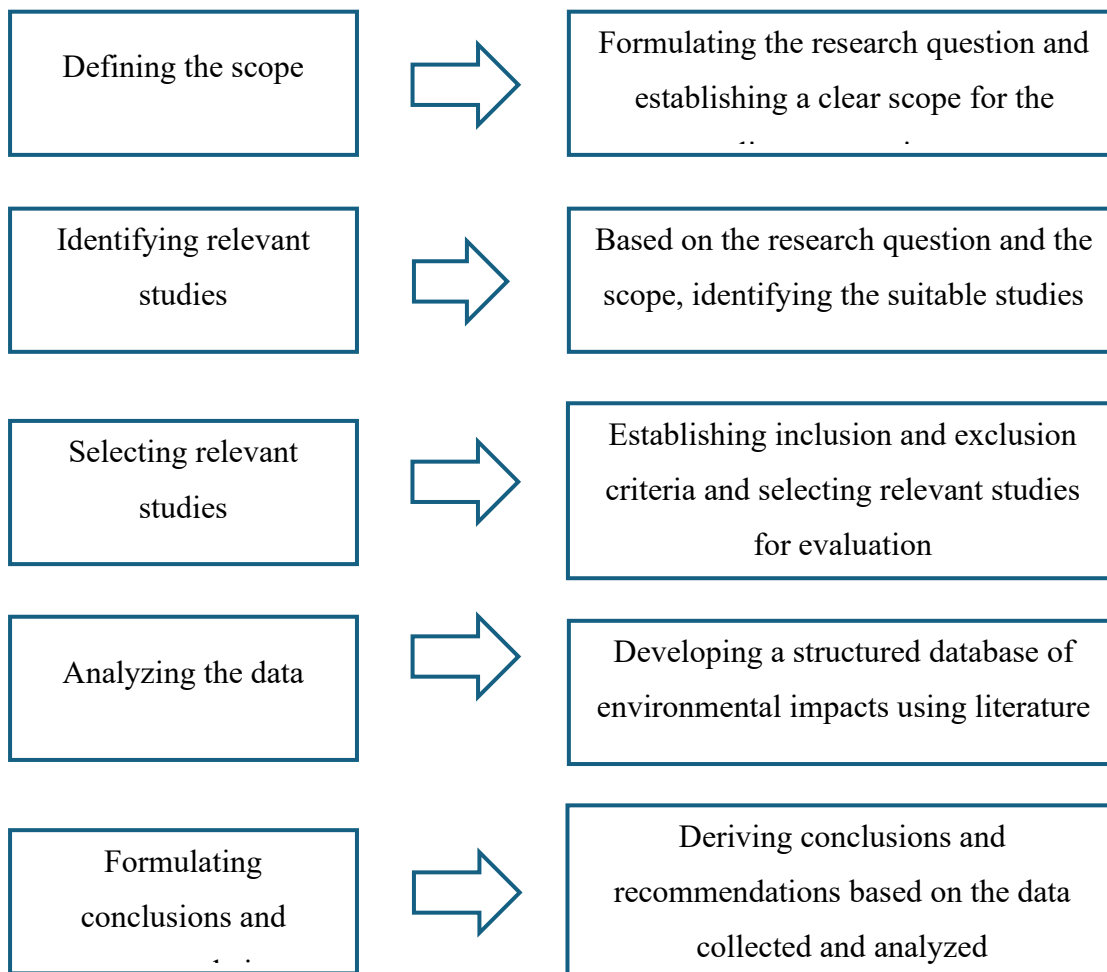


FIGURE 2.1 : CONCEPTUAL FRAMEWORK OF THE RESEARCH

2.2. Scope Definition

Initially, defining the research question and the scope of the literature review was to be carried out. As mentioned in the introductory section, this study seeks to address the research questions: '**RQ1:** Which established methodologies can be used to assess these impacts in the context of e-grocery logistics? **RQ2:** What are the environmental impacts of e-grocery distribution networks across different categories? Therefore, three elements of the research question were identified as important in order to critically examine the specified research question. These elements included 'environmental impact', 'E-grocery', and 'distribution network'. This was followed by

selecting keywords for each of these elements. When considering the study scope, the significance of the quantitative measurement of the E-grocery's environmental impact throughout the entire supply chain, including the last-mile, was underscored.

2.3. Identifying and Selecting Relevant Studies

To ensure a proper standard of the reviewed articles was maintained, 'Scopus' was selected as the scientific database in the field of logistics. A comprehensive search was conducted by using this platform about the identified research question and scope. This was facilitated by identifying keywords for the aforementioned three elements, which are shown in the following table.

TABLE 1: KEYWORDS FOR THE SELECTED THREE ELEMENTS

Environmental Impact	E-grocery	Distribution Network*
Carbon footprint	E-commerce	Last mile delivery
Life Cycle Assessment	Online grocery	First-mile delivery
LCA	E-retailing	Middle-mile delivery
Sustainability impact	E-tailing	Logistic*
Carbon emission	Electronic commerce	Supply chain*

In the process of conducting an SLR, constructing a comprehensive and precise search string is considered of utmost importance. This contributes to the easy and accurate retrieval of the most relevant and exhaustive set of research from academic databases. In this regard, Boolean operators such as AND, OR, and NOT are extensively used, which facilitate combining or excluding specific keywords and phrases, establishing refinement and structuring of the study findings (Alharbi & Stevenson, 2020). Taking this into consideration, a search string was constructed by using Boolean operators in which the above defined keywords were combined. For the keywords within one

particular category, the operator 'OR' was used, whereas for the keywords between two or more categories, the operator 'AND' was used. This strategy broadens the scope of the review while maintaining relevance to the research question (Arevalo-Ascanio et al., 2025). Moreover, it was required to capture both singular and plural terms for some selected keywords. For this, a stemming tool was utilized in the search string, which is depicted by an asterisk (*) as shown in the above table. Therefore, the search string used for the SLR is; *'carbon footprint' OR 'LCA' OR 'Life Cycle Assessment' OR 'environmental impact' OR 'sustainability impact' OR 'carbon emission' AND 'E-grocery' OR 'E-commerce' OR 'online grocery' OR 'E-retailing' OR 'E-tailing' OR 'electronic commerce' AND 'distribution network*' OR 'last-mile delivery' OR 'first-mile delivery' OR 'logistic' OR 'supply chain' OR 'middle-mile delivery'*.

When selecting studies for the SLR, certain specifications were considered. The literature search was restricted to publications only in the English language. This guaranteed precise and accurate comprehension, critical evaluation, and synthesis of study findings. Moreover, since the author is proficient in English, misinterpretation of data due to language barriers was expected to be prevented by this criterion, thus leading to consistency in data extraction and analysis. Additionally, access to high quality literature was achieved by this. To obtain a global perspective of the environmental impacts of the E-grocery distribution networks, no geographical limitations were set for the selection of articles for the review. This enabled a comprehensive appraisal of diverse logistical models, consumer behaviors, and environmental conditions across different settings, which facilitated the formulation of more generalized conclusions. Furthermore, the review only included journal articles, conference proceedings, and book chapters, explicitly excluding certain subject areas such as chemistry, physics, astronomy, material science, medicine, arts, humanities, multidisciplinary, and psychology. A wide array of scholarly discussions as well as methodologies related to the study scope could be accessed by reviewing literature only from the above-mentioned sources. Moreover, this enabled

incorporating well established study findings as well as novel, emerging insights into the research topic. To maintain relevance regarding the study scope, those subject areas deemed outside the scope were explicitly excluded. Thus, topics more closely aligned with the study area, such as environmental science, logistics, supply chain management, etc., were given more focus.

Upon defining these criteria, a database search was conducted in March 2025. Originally, 299 articles were obtained from the search. It was required to identify only the relevant studies from those articles, which was achieved by two phases in which selection criteria were applied. The first phase consisted of a screening process where the title and the abstract of the selected scholarly publications were reviewed, thereby reducing the sample to 216 papers. The entire text of the articles short-listed in this phase was then reviewed in the second phase in order to ensure their relevance and maximize specificity, which resulted in 178 articles, thus arriving at the final sample. Here also, certain expulsion criteria were established to maintain focus on the research objectives. These include studies focusing;

- solely on e-commerce without addressing the environmental impacts or sustainability impacts,
- on economic analysis and consumer behavior related to environmental impact,
- on E-commerce (apparel, fashion, electronics) without mentioning E-grocery,
- on financial performance, business models, and market trends without reference to environmental impacts.

Even though no specific time period was defined for the articles initially, results were obtained from the literature dating from 2000 to 2025. A summary of this literature review is depicted by the following Figure 2.

2.4. Data Analysis

The data analysis was carried out systematically to extract, organize, and synthesize relevant data from the final sample. Following the second phase of the literature review, information in all the selected articles was categorized into several sections and was imported into a well-structured Excel sheet to facilitate transparent comparison and analysis.

The extracted data includes the following key elements, with reference to the study objective.

1. Article Title - to catalog sources
2. Authors - to identify prominent contributors in the field
3. Journal - to assess publication quality and relevance
4. DOI - to enable traceability and citation
5. Publication Year - to evaluate temporal trends
6. Considered Environmental Impact - to determine the specific environmental factors assessed
7. Delivery Model - to examine the distribution strategies
8. Methodology - to assess the rigor and comparability of findings
9. Assumptions and Limitations - to critically evaluate the strength of evidence
10. Key Findings - to extract the main outcomes related to the environmental impact
11. Impact Values (Quantitative) - to enable numeric comparison across studies
12. Technologies Used - to identify innovations and practices influencing sustainability

13. Geographical Context - to understand the regional applicability of findings

After gathering the above-mentioned information, the data analysis was conducted systematically to identify key information, impact values, and gaps relevant to the research objective.

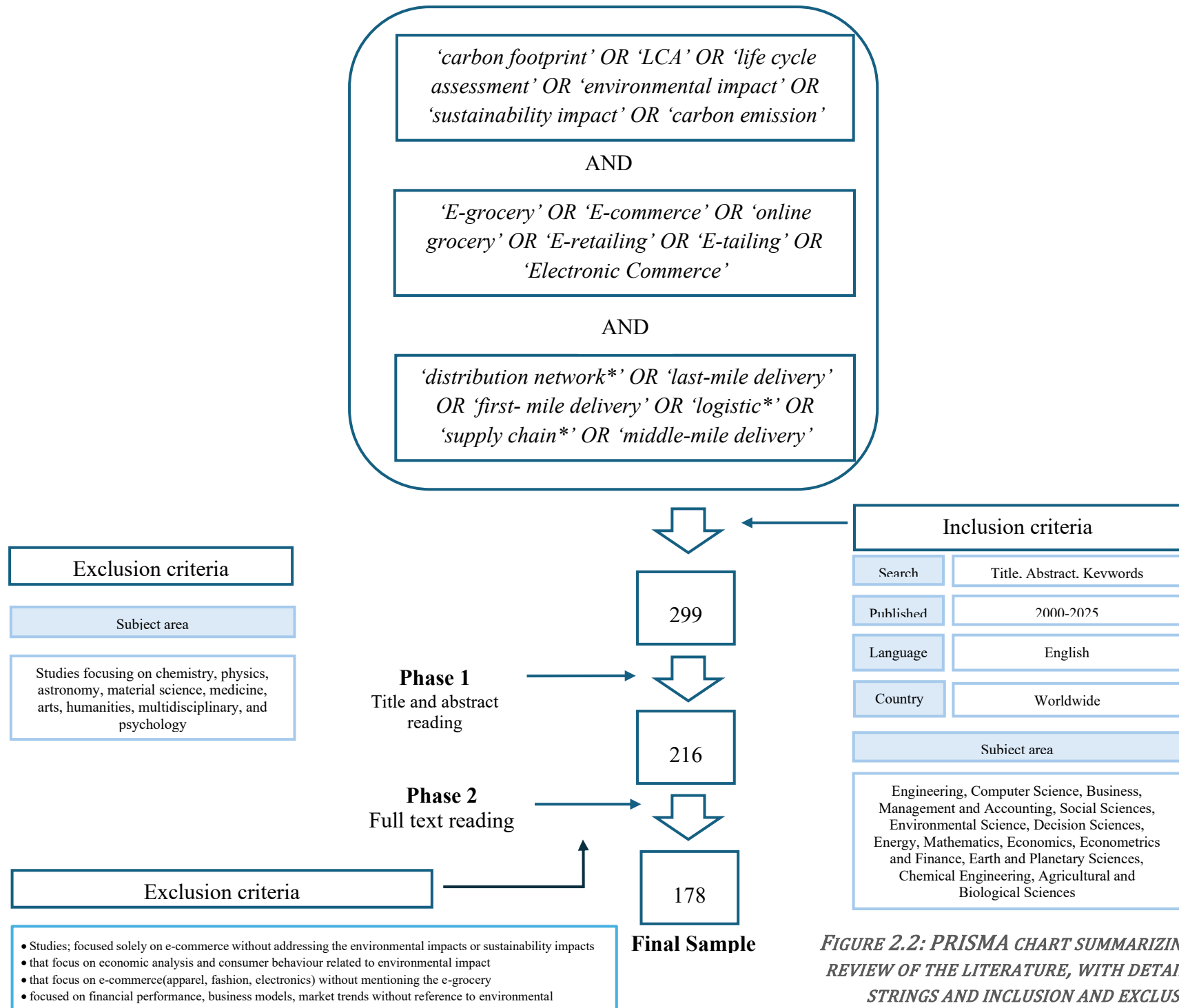


FIGURE 2.2: PRISMA CHART SUMMARIZING THE SYSTEMATIC REVIEW OF THE LITERATURE, WITH DETAILS ON THE SEARCH STRINGS AND INCLUSION AND EXCLUSION CRITERIA

3. Results

In this chapter, the research questions ‘**RQ1:** Which established methodologies can be used to assess these impacts in the context of e-grocery logistics? **RQ2:** What are the environmental impacts of e-grocery distribution networks across different categories?’ will be addressed based on the results of the analysis.

A total of 178 studies were selected through a systematic literature review process, encompassing journal articles, conference proceedings, and book chapters. These studies examine various modelling approaches and network structures employed in e-grocery distribution, including last-mile delivery, omnichannel strategies, crowd logistics, and dual-channel systems. The analysis integrates both quantitative emission metrics (CO₂ emissions data and energy consumption) and qualitative model attributes (methodologies and regions) to provide a multidimensional understanding of sustainability performance.

The results are organized into the following key categories;

- Logistic Infrastructure
- Transport Operations
- Product Specific Logistics
- Operational and Technological strategies

Each category synthesizes evidence from the selected literature, highlighting quantitative emission performance. Cross-dimensional analysis reveals how combinations of network design, delivery model, and vehicle technology create a compound effect on environmental performance. To address RQ1, each section highlights the methodologies that were used to measure the environmental impacts as mentioned in the selected literature.

3.1. Logistic Infrastructure

3.1.1. Environmental Impact Metrics and Assessment Methods in Network Structure

The structural configuration of a distribution network, whether centralized, decentralized, or hybrid, plays a crucial role in considering certain aspects (Sahay & Ierapetritou, 2014). To answer RQ1, A route planning method for cross border e-commerce logistics of agricultural products is developed using a recurrent neural network model. This approach analyzes travel time data along logistics routes to optimize the selection of low-carbon distribution routes for fresh agricultural products. The methodology integrates CO₂ emission estimation into the route planning process by considering time dependent vehicle speeds, distances, and emission factors, enabling the identification of environmentally efficient delivery options(Teng, 2021). According to Van Loon (2015), a Life Cycle Assessment model was developed to evaluate and compare the environmental impact of various fulfillment methods for fast-moving consumer goods in the United Kingdom. To determine the CO₂ emissions and other environmental impacts associated with each model, the ReCiPe impact assessment method is applied using the SimaPro software. This methodology enables a quantitative comparison of carbon footprints and overall environmental impacts across different fulfillment strategies.

To provide answers to RQ2, in centralized distribution networks, CO₂ emissions are determined by the delivery vehicle type and the routing efficiency. Centralized van delivery results in emissions of around 2 kg CO₂ equivalent per item (single product) (Van Loon et al., 2015). Passenger vehicles emit approximately 0.417 kg of CO₂ equivalents per mile, while delivery trucks emit around 1.0683 kg of CO₂ equivalents per mile (Belavina et al., 2017).

In the United States, 0.23 kg of CO₂ per mile is emitted in decentralized systems (Li & Shih, 2024). According to Yang et al. (2023), the focus is solely on emissions from on-

road operations. Due to the lack of a delivery route simulation, truck trajectories are unavailable. Therefore, Greenhouse gas emissions are estimated using the Environmental Protection Agency's light truck emission factor of 234 grams of CO₂ per mile. During peak season, daily emissions in New York City (NYC), United States, reach 16.11 metric tons of CO₂ equivalent, not only from e-grocery (Yang et al., 2023). In the Chinese context, 2738.06 kg of CO₂ is emitted when having 10 distribution centers (Shi et al., 2022a).

In Hybrid systems, diesel trucks emit 18 g of carbon monoxide, 67.5 g of hydrocarbons, and 0.5 g of nitrogen oxides per trip in Aachen, Germany (Ghazal et al., 2025). Production emissions also play a key role; an autonomous delivery robot (ADR) generates 4.5 tons of CO₂ equivalent, while an electric light commercial vehicle (LCV) has a higher embedded footprint of 10.4 tons of CO₂ equivalent. Moreover, in Hamburg, an internal combustion engine LCV consumes 205 Wh per parcel, compared to 98 Wh for an electric LCV. Similarly, in Barcelona, energy consumption drops from 290 Wh to 140 Wh electric LCV (Lemardelé et al., 2023). Emission conversion factors are used to determine the quantity of CO₂ emitted during the process (Lemardelé et al., 2023). Considering hybrid systems for the RQ1, according to Ghazal et al. (2025) Life Cycle Assessment, following ISO 14040/14044 standards, is used to evaluate the environmental impacts of a product system across its entire life cycle. To assess CO₂ emissions, life cycle inventory data on input and output flows (e.g., energy, materials, emissions) are collected and translated into environmental impacts using an impact assessment method. In this study, the ReCiPe approach is applied, with a primary focus on Global Warming Potential.

3.1.2. Environmental Impact Metrics and Assessment Methods in Last Mile

Infrastructure

This section examines the physical endpoints and methods involved in the final handoff of e-groceries, including home delivery, click and collect, parcel lockers,

pickup points, store-based pickup, crowdsourcing, unattended home delivery, and failed delivery. Home delivery remains the most prevalent e-grocery fulfillment mode, accounting for approximately 50% of all online grocery orders (Gatta et al., 2021).

Focusing on RQ2, in Norway, this mode generates 0.24 kg CO₂ per parcel and 10.88 kg CO₂ per delivery trip, and CO₂ emissions are calculated based on average fuel consumption, distance traveled, and the emission factor for fossil diesel (2.67 kg CO₂ per liter) (Hovi & Bø, 2024). For light commercial vehicles, the average emission rate for home delivery is approximately 228 g of CO₂ equivalent per vehicle km traveled. Greenhouse gas emissions are calculated based on traveled distances using an average emissions factor per unit distance. (Marcucci et al., 2021).

Click and collect infrastructure, commonly referred to as click & pick, a store based pickup represents an emerging but comparatively less dominant last-mile solution, accounting for approximately 10% of e-grocery market share across countries such as the United Kingdom, Germany, the United States, Norway, Morocco, and Italy (Aziz et al., 2022). In the United Kingdom, van-based home delivery and in-store pick-up methods generate approximately 200 g of CO₂ equivalent per item (Van Loon et al., 2015). In Norway, click & pick operations were reported to generate 11,491.5 km of weekly travel distance, reflecting their logistical footprint within national fulfillment networks (Marcucci et al., 2021). Simulation based analyses conducted in London, UK, indicate that click & pick models can contribute to distance reductions of up to 18% and time savings of up to 21%, particularly when strategically integrated with customer density and urban infrastructure (Zissis et al., 2018). In the context of Switzerland, simulation based studies reveal that click and collect models involving customer pickup by car or delivery to parcel lockers are rarely the most environmentally favorable option. Moreover, home delivery consistently outperforms click and collect in terms of hydrocarbon and carbon monoxide emissions, and is

identified as the optimal delivery method for 80% to 93% of neighborhoods when all supermarkets and households are included in the model (Schnieder et al., 2023).

To address RQ1, Emissions are estimated using the Handbook Emission Factors for Road Transport (HBEFA 4.1), which provides a comprehensive set of emission factors based on variables such as vehicle type, routes, traffic conditions, start modes (cold/warm), climate, road type, speed limits, and year (Schnieder et al., 2023). Trott et al., (2020) developed a model to estimate the emissions. To quantify CO₂ emissions from private and commercial traffic, this study employs an emission model that converts distance metrics generated from simulation studies into emission values. The emissions ($E_{i,j}$) are calculated using the formula;

$$E_{i,j} = \sum N_{j,k} \times M_{j,k} \times EF_{i,j,k} \quad (1)$$

where:

- $N_{j,k}$ - number of vehicles in the nation's fleet for category j and technology level k ,
- $M_{j,k}$ - average annual mileage (in km) for each vehicle category and technology,
- $EF_{i,j,k}$ - technology specific emission factor for pollutant i (CO₂) for vehicle category j

Customer pickups using gasoline vehicles, as observed in Ohio and Pennsylvania, USA, produce 8.887 kg of CO₂ per gallon (Brown & Guiffrida, 2014). According to Brown & Guiffrida, (2014a) the total CO₂ emissions (C) are then computed by;

$$C = cF = \frac{cD}{f} = \frac{16cnPR}{3\pi f} \quad (2)$$

- F - the total fuel consumed (in gallons)
- f - the average fuel economy (in miles per gallon)
- D - the total distance travelled for n customers
- n - the number of customers
- P - the proportion of customer travel attributed to the depot
- R - the radius of the customer demand region

In relation to RQ2, parcel locker infrastructure has significant potential for emission reduction in urban last-mile delivery systems. In Norway, the use of parcel lockers results in an average of 0.18 kg of CO₂ emissions per parcel and 22.82 kg of CO₂ per delivery trip (Hovi & Bø, 2024). While in Germany, simulation studies show that deploying electric trucks in combination with parcel and lockers can lead to a 63.6% reduction in CO₂ emissions and a 5.4% decrease in total costs (Ghazal et al., 2025). In Norway, pickup point deliveries result in 0.09 kg of CO₂ emissions per parcel and 70.54 kg CO₂ per delivery trip (Hovi & Bø, 2024). In Sicily, Italy, the geographical clustering of pickup points has also resulted in population coverage gaps, especially in rural and low-density areas (Russo et al., 2023). However, evidence from Sri Lanka shows that well distributed pickup points can significantly reduce delivery efficiencies and reduce the distance traveled up to 42%, which directly contributes to last-mile emissions (Ranathunga et al., 2022). Crowdsourced last-mile delivery in Rome, Italy, combined with automated parcel lockers, is estimated to reduce CO₂ emissions by 1,098 tonnes annually, with a range of 304 to 1,215 tonnes. At the same time, other pollutants also show measurable decreases with 239 kg of Particulate Matter reduced per year, 3.76 tons of Nitric oxide, and 2.24 tons of carbon monoxide per year (Gatta et al., 2019). Importantly, 19.2% of surveyed consumers (192 out of 1000) expressed interest in adopting crowdsourced last-mile delivery (Cano et al., 2022). Crowdsourcing can serve as a viable strategy for reducing urban congestion, vehicle emissions, noise, and traffic-related waste, while also improving last-mile delivery economics (Alejandra Maldonado Bonilla et al., 2024a).

To answer RQ1, Gatta et al. (2019) apply the COPERT 5.1.1 model (Computer Program to Calculate Emissions from Road Traffic, developed by EMISIA SA) to estimate the environmental benefits resulting from reduced air pollutant emissions. The model calculates reductions in particulate matter, nitrogen oxides, carbon monoxide, and carbon dioxide, thereby addressing both local (urban air quality) and

global (greenhouse gas) impacts. For each public transport vehicle i , total emissions are computed as the sum of three components;

$$E_i = E_{hot,i} + E_{cold,i} + E_{evap,i} \quad (3)$$

- $E_{hot,i}$ - emissions during normal engine operation (hot phase)
- $E_{cold,i}$ - emissions during engine warm-up (cold start)
- $E_{evap,i}$ - evaporative emissions, primarily non-methane volatile organic compounds

According to Eliyan et al., (2021a) total carbon emissions are divided into two components in smart parcel stations: Retailer Carbon Emissions (RE) and Customer Carbon Emissions (CE), calculated as follows;

$$RE = \sum_{i \in N} \sum_{j \in N} \gamma_R TD_{ij} x_{ij} \text{ (kg CO}_2\text{)} \quad (4)$$

$$CE = \sum_{k \in K} \sum_{j \in J} \gamma_c TD_{ij} x_{ij} \text{ (kg CO}_2\text{)} \quad (5)$$

- γ_R and γ_c are the CO₂ emission factors (kg CO₂ per unit distance) for the retailer's delivery truck and customer vehicles, respectively
- TD_{ij} - travel distance between locations i and j
- x_{ij} - binary or fractional decision variable indicating whether travel between i and j occurs
- N - set of delivery locations, K is the set of customers, and J represents parcel station locations.

In response to RQ2, in Norway, unattended home delivery results in 0.25 kg of CO₂ emissions per parcel and 15.70 kg of CO₂ per delivery trip (Hovi & Bø, 2024). On the other hand, United Kingdom parcel delivery returns generate approximately 66 g of CO₂ equivalent per item, while failed delivery attempts through parcel delivery services account for 62-89 g of CO₂ equivalent per item. However, failed deliveries via van-based systems have a significantly lower impact, estimated at just 0.004 g of CO₂ equivalent per item, due to consolidated routes and lower marginal emissions per unit (Van Loon et al., 2015).

3.1.3. Environmental Impact Metrics and Assessment Methods Based on Packaging

Packaging materials contribute significantly to the overall environmental impact of e-grocery systems. The following section addresses RQ2 regarding the packaging material. In Europe, the carbon emission factors for commonly used packaging materials are substantial; polypropylene emits 2.53 kg CO₂eq/kg, polyester emits 6.64 kg CO₂eq/kg, glass accounts for 5.76 kg CO₂eq/kg, cardboard emits 2.52 kg CO₂eq/kg, and cleaning agents associated with reusable packaging add 1.71 kg CO₂eq/kg. Additionally, electricity consumption used in cleaning and handling reusable packaging contributes 0.11 kg CO₂eq per kWh. Most notably, polyester emits approximately 215% more CO₂ than cardboard, highlighting the importance of material selection in packaging design. However, reusable packaging often becomes environmentally preferable to single-use alternatives after just 1 to 3 reuse cycles (González Romero et al., 2024a). In the context of packaging in China, various materials contribute differently to direct carbon emissions during production. Plastic bags have the highest emission factor at 3.240 kg CO₂eq/kg, followed by tape at 2.765 kg CO₂eq/kg, woven bags at 2.507 kg CO₂eq/kg, and green plastic bags designed to meet national sustainability criteria at 1.274 kg CO₂e/kg. Air bubble bags exhibit the lowest emissions, at just 0.363 kg CO₂eq/kg (Jiang et al., 2023). Innovative packaging solutions have significant potential to reduce the environmental impact of e-grocery and retail logistics. Reusable packaging systems can reduce CO₂ emissions by up to 80% and are fully recyclable, and making them a strong alternative to single use packaging. On the other hand, recycled cardboard offers resource savings, including a 30% reduction in electricity and a 1% decrease in water consumption per ton of material produced. In the beverage sector, flat wine bottles have emerged as a lightweight alternative to traditional glass, reducing packaging weight by 87%, and contributing to lower transportation emissions. On the energy side, paper bags offer

a significant advantage, using 80% less energy than standard corrugated boxes. (Escursell et al., 2021).

In relation to RQ1 Kang et al., (2020) to determine CO₂ emissions from intracity express delivery services, the study employed a systematic model incorporating three key methods: estimation of transportation distance based on delivery mode and phase, characterization of delivery volume and weight data for parcels, and application of carbon emission factors derived from the GaBi life cycle assessment database, tailored to various transportation modes within the Chinese commercial context.

3.2. Transport Operations

3.2.1. Environmental Impact Metrics and Assessment Methods Based on Vehicle

This section presents a comparative evaluation of environmental performance across various vehicle types used in e-grocery distribution networks. Vehicle choice significantly influences last-mile emissions, energy consumption, and sustainability. The analysis is consistent with quantitative emission values for Internal Combustion Engine (ICE) Vehicles, Electric Vehicles, and Drones. ICE vehicles typically include diesel trucks or vans used for the delivery purpose of the last-mile infrastructure. While in Europe, vans emit 0.33 kg of CO₂ per km (González Romero et al., 2024b). More specific data from Italy show that diesel vans produce around 331 g of CO₂ equivalent per km (Temporelli et al., 2022a), aligning closely with generalized van emission estimates of 0.23156 kg CO₂e/km across the region (Ekren et al., 2024). In Austria, a van only delivery system operates in Innsbruck city, resulting in a total emission load of 242 kg CO₂ per day (Büttgen et al., 2021), and emissions estimates from the United States provide further context. Car emissions average 3.369 kg CO₂/km in urban settings such as the San Francisco Bay Area, California (Qi et al., 2018).

To answer RQ1, according to Montaña et al., (2022b) total CO₂ emissions were calculated by using the MEET (Methodologies for Estimating Emissions from Transport) framework. This methodology determines the CO₂ emission rate (in g/km) using a speed dependent regression model. The model considers key factors such as the vehicle's weight (curb weight + payload) and assumes standardized test conditions, including a flat road gradient and an unloaded vehicle. Emissions are calculated as a function of the vehicle's average speed under these conditions.

Ekren et al., (2024a) suggest a model for the emission per basket for each simulation run. "ru" is calculated as follows;

$$EB_{ru} = e_{van} \times (d_i \times d\% + pick_in_middle_{ru} \times d_{ij} + pick_in_farthest_{ru} \times d_{iz}) + go_buy_{ru} \times e_{car} \times 2 \times d_{local} \quad (6)$$

- EB_{ru} - Emission per basket in simulation run ru
- e_{van} - Emission factor for delivery van (kg CO₂ per km)
- d_i - Distance from depot to customer i
- $d\%$ - Share of distance allocated per basket
- $pick_in_middle_{ru}$ - Binary variable (1 if a basket is picked from an intermediate depot, 0 otherwise)
- d_{ij} - Distance from main depot to intermediate depot j
- $pick_in_farthest_{ru}$ - Binary variable (1 if a basket is picked from the farthest depot z , 0 otherwise)
- d_{iz} - Distance from depot z to customer i
- go_buy_{ru} - Binary variable indicating if the customer performs additional shopping (1 = yes, 0 = no)
- e_{car} - Emission factor for a private car (kg CO₂ per km)
- d_{local} - Average distance to the nearest grocery store

To address RQ2, studies conducted in the Aachen region of Germany and Italy, the energy and environmental performance of electric trucks, electric vans, plug-in hybrid vans, and electric cargo bikes (e-cargo bikes) was evaluated under last-mile delivery

conditions. The average energy consumption of electric trucks was recorded at 0.296 kWh/km, while e-cargo bikes consumed only 0.0113 kWh/km (Ghazal et al., 2025), highlighting their considerable energy efficiency. In terms of carbon emissions, e-cargo bikes demonstrated the lowest impact, emitting between 79–80 grams of CO₂ equivalent per km, followed by electric vans at 158 g CO₂-eq/km, and plug-in hybrid vans at 246 g CO₂-eq/km (Temporelli et al., 2022b).

Photochemical ozone formation, measured in non-methane volatile organic compounds (NMVOC) equivalents, further illustrates these differences: plug-in hybrid vans generated 0.448 g NMVOC-eq/km, electric vans emitted 0.310 g NMVOC-eq/km, and e-cargo bikes produced the least, ranging between 0.178–0.182 g NMVOC-eq/km. Regarding resource consumption, plug-in hybrid vans used 3.25 MJ/km, electric vans consumed 1.89 MJ/km, and e-cargo bikes required only 0.842–0.862 MJ/km. Similarly, in the category of mineral and metal resource use, electric vans consumed 3.88×10^{-6} kg Sb equivalents per kilometer, while e-cargo bikes demonstrated significantly lower values, between $7.06\text{--}7.34 \times 10^{-7}$ kg Sb-eq/km (Temporelli et al., 2022b).

Findings related to RQ1 indicate that Temporelli et al., (2022b) developed a model to calculate the non exhaust particulate emissions in electric bikes and diesel vans,

$$\mathbf{Road\ Wear\ emission} = \mathbf{C_{road}} \times \mathbf{GVW} \quad (7)$$

$$\mathbf{Tyre\ Wear\ emission} = \mathbf{C_{tyre}} \times \mathbf{GVW} \quad (8)$$

$$\mathbf{Break\ Wear}_{ICE} = \mathbf{C_{break}} \times \mathbf{GVW} \quad (9)$$

$$\mathbf{Break\ Wear}_{EV} = \mathbf{SF_{break}} \times \mathbf{C_{break}} \times \mathbf{GVW} \quad (10)$$

- GVW - Gross Vehicle Weight = Curb weight + Passenger weight
- C_{road} - Road abrasion coefficient = 9.79×10^{-9} kg/kg_{vehicle}
- C_{tyre} - Tyre abrasion coefficient = 5.73×10^{-8} kg/kg_{vehicle}
- C_{break} - Brake friction coefficient = 4.45×10^{-9} kg/kg_{vehicle}
- SF_{break} - Scaling factor for brake wear in electric vehicles = 0.2

3.2.2. Environmental Impact Metrics Based on Delivery Time

A case study conducted in China led to a 14% reduction in total travel distance, with significant improvements in carbon emissions based on departure time selection. By shifting deliveries to off peak periods, by doing that shifting emissions were reduced from 117.91 kg to 84.70 kg, with the optimal departure time identified as 12:30 PM. A comparison of emissions across different departure times revealed the following: 6:30 AM – 81.27 kg, 7:30 AM – 110.92 kg, 8:30 AM – 117.91 kg, and 12:30 PM – 84.70 kg.

3.3. Product Specific Logistics

3.3.1. Environmental Impact Metrics and Assessment Methods in Cold Chain

Logistics

Route optimization in China's cold chain logistics reduced emissions from 476 kg to 413 kg, demonstrating the effectiveness of optimized delivery routes in enhancing environmental sustainability (Teng, 2021).

To address RQ1, Shi et al. (2022b) identify two primary sources of carbon emission: emissions from fuel consumption, which include both transportation and temperature control, and emissions resulting from electricity usage at distribution centers (DCs). The overall carbon emissions of the cold chain logistics scheduling system within a given time period are expressed through the following formulation;

$$E_{CO_2} = \sum_{m \in D} \sum_{k \in K_m} \sum_{i \in L} \sum_{j \in L} o_m u_{mk} x_{ij}^{mk} E_f + \sum_{m \in D} o_m E_e \quad (11)$$

- D - Set of candidate distribution centers (DCs)
- K_m - Set of vehicles available at DC
- L - Set of all nodes, including both DCs and retail
- x_{ij}^{mk} - Binary decision variable; 1 if vehicle k from DC m travels from node i to j , 0 otherwise
- u_{mk} - Fuel consumption per unit distance or per trip by vehicle k from DC m
- E_f - CO₂ emission factor per unit of fuel (e.g., kg CO₂ per liter of fuel)

- O_m - Binary decision variable; 1 if DC m is selected for operation, 0 otherwise
- E_e - CO₂ emissions from electricity used at DC m

3.4. Operational and Technological Strategies

3.4.1. Optimization Approach

Optimization in e-grocery logistics is to manage cost, service level, and environmental impacts. Researchers apply diverse methodologies from traditional mathematical models like Mixed Integer Linear Programming (MILP) to more advanced strategies like Machine Learning, Agent-Based Learning, and Game Theoretic Optimization. These methodologies help to optimize routing, inventory, time-slot scheduling, and last-mile delivery under various degrees of complexity, uncertainty, and sustainability (Clement & Spinler, 2025, Alejandra Maldonado Bonilla et al., 2024b).

To answer RQ2, recent studies from Europe demonstrate the practical effectiveness of MILP in reducing environmental impact within e-grocery logistics. In the Walloon region of Belgium, MILP was applied to optimize parcel distribution by designating previously clustered districts as sink locations, final destinations for deliveries in a multi-echelon network. This structured routing results in a carbon emissions reduction of up to 35.5% (Arevalo-Ascanio et al., 2025). Similarly, in Monza, Italy, a comparative MILP model was used to optimize two scenarios: a cost-only optimization and an integrated cost-environmental approach. While the cost-efficient model focused solely on minimizing costs, the other scenario included both monetary and environmental objectives within the optimization framework. This integration achieved a remarkable 93.8% reduction in carbon emissions, lowering the environmental impact to just 379.92 kg CO₂-equivalent per year (Tudisco et al., 2025). These Metaheuristics, Game theory optimization modeling, Algorithmic route optimization, and mathematical modeling are used to optimize the different scenarios. In conclusion, the findings presented as above align with the stated research questions and the overall objective of the study. Through the analysis conducted, the author

successfully identified and characterized the key environmental impacts associated with E-grocery logistics across the last-mile stage of E-grocery distribution. These results help to clarify how variations in environmental performance are caused by different operational practices and delivery configurations. Furthermore, the results have highlighted and evaluated several established methodologies applicable for assessing these impacts within an e-grocery context, thereby addressing the second research question. Together, these outcomes provide an integrative perspective on environmental sustainability regarding the E-grocery logistics, thus contributing to bridging the identified knowledge gap. The following discussion, which further interprets the implications of these findings for the development of more sustainable and effective e-grocery distribution systems, is firmly based on the insights gained from this analysis.

4. Discussion

This study was undertaken to find a method to effectively measure the environmental impact of E-grocery distribution networks across varying delivery models and operational practices. Numerous delivery models, operational practices along with their technological integrations, were assessed by analyzing 178 resources and the results were categorized under several topics, including the logistic infrastructure, transport operation, product specific logistics, operational and technological strategies. This categorization supported the author in arriving at an interpretation of how individual and combined factors influence the environmental sustainability of the delivery methods. Moreover, the analysis of the resources paved the way for not only contextualization of them within the assumptions and limitations, but also quantification of the emissions and energy consumption as an outcome. Therefore, this section focuses on interpreting these patterns in the context of the current literature, evaluating the implications for sustainable E-grocery operations, and identifying the major areas where methodological or technological advancements could further mitigate environmental impacts.

The results are organized into four categories to ensure conceptual clarity and analytical consistency. Logistic Infrastructure captures the structural and physical design elements of e-grocery distribution, such as network configuration, last-mile infrastructure, and packaging, which form the backbone of distribution systems. Network configuration directly influences the delivery speed, lead time, and emissions (Melkonyan et al., 2020). Last-mile infrastructure is the most challenging and impactful stage for a sustainable e-grocery operation due to logistic costs and emissions (Siragusa et al., 2022). Packaging is considered because it not only safeguards products, but also significantly affects vehicle load efficiency, waste generation, and environmental impact in grocery items (Accorsi et al., 2015). Transport Operations focuses on the mobility dimension, including vehicle choice and

delivery scheduling, which directly determine emissions from freight movement. Product specific logistics is separated as temperature sensitive goods, particularly chilled and frozen products, require distinct handling. Finally, Operational and Technological Strategies encompass optimization approaches and decision support methods that enhance efficiency and reduce environmental impacts across the system.

4.1. Logistic Infrastructure

4.1.1. Environmental Impact Metrics and Assessment Methods in Network Structure

The following section presents an overview of the network structures employed in e-grocery distribution, followed by a discussion of their environmental impacts and the methodologies that they used to assess the impacts.

Three key types of network structures were focused on by the author, namely centralized, decentralized and hybrid, which present their own influences on the environmental performance, exhibiting distinct trade-offs. Among those, centralized distribution networks show heightened sensitivity to vehicle type and routing efficiency. In the context of E-grocery, centralized distribution includes the processing and dispatching of ordered goods from a centralized facility such as a central warehouse or a manufacturer's hub. As shown in the results section, (Van Loon et al., 2015) reports that high emissions of around 2 kg CO₂ equivalent per item occur in centralized van delivery, followed by 0.417 kg of CO₂ equivalents per mile for passenger vehicles. It should be noted that in this context, the term 'item' refers to a single consumer product within a shopping basket. This is used as the functional unit in determining the Life Cycle Assessment (LCA) which will be discussed in detail at the latter parts of this section. Therefore, the aforementioned stresses on the importance of route optimization and fleet electrification as suggested by (Teng, 2021) regarding the cold chain transportation in China, where 13% emission reduction was

resulted by route optimization. These results perfectly align with earlier findings that state economies of scale in transportation can be achieved by combining trips together but higher last-mile emissions are also a possibility in cases of inefficient routes and outdated vehicle technologies (Sahay & Ierapetritou, 2014).

When analyzing environmental implications of distribution systems, United States often bears a primary focus due to being one of the largest and most mature E-grocery markets. Among many others, this reason plays a significant role in the country's challenges in GHG emission reduction goals. Moreover, the country possesses advanced logistic infrastructure shaped by regulations, comprehensive life cycle inventory (LCI) data and established emission factors, paving the way for rigorous case studies in quantifying environmental impacts (Reichmuth et al., 2013). Such a study has been carried out in US regarding the decentralized systems which creates an opposite picture than in centralized systems. Decentralized systems include the products being stored and fulfilled from multiple local warehouses or distribution centers rather than from a single central facility. When looking at the previous examples related to decentralized systems, even though reductions in the delivery distances can be performed, they do not necessarily result in reduced emissions. As mentioned previously, estimates indicated by a research study carried out in US shows comparatively modest levels of CO₂ outputs per mile (0.23kg) but also indicate high aggregate emissions during peak seasons with emissions reaching 16 metric tons of CO₂ equivalents per day within the New York City (Li & Shih, 2024a) (Yang et al., 2024). But, as shown by (Shi et al., 2022) multi-node channel in China, higher number of distribution centers may cause less transport emission per unit distance but also has the possibility of resulting in higher operational energy and other impacts related to infrastructure-building.

This leads to the hybrid models that exhibit integrations of both centralized and decentralized systems. Hybrid model refers to a configuration including parts from both centralized and decentralized models that includes a central warehouse that acts

as a primary fulfillment hub along with a regional or local micro fulfillment center to support enhanced last-mile delivery efficiency. As demonstrated by (Ghazal et al., 2025) and (Lemardelé et al., 2023) electric light commercial vehicles (LCVs) have the potential of lowering the per parcel energy significantly compared to internal combustion equivalents; which go by 98Wh and 205Wh in Hamburg as been shown in the examples. But, this also goes with saying that the life cycle impacts of the vehicle production should also be taken into consideration. Those LCVs can also be compared with autonomous delivery robots (ADRs) that indicate low operational energy demands, but they also exhibit substantial amounts of embedded emissions compared to electric LCVs. These findings point out that hybrid delivery networks may optimize operational emissions through technology integration, but embedded impacts and end-of-life considerations remain underexplored.

In the previous section, network structures of an e-grocery distribution were presented and now followed by a detailed description of the methodology used to quantify their environmental impacts. This approach directly links each network design to its assessed outcomes. As has been demonstrated by (Ghazal et al., 2025), the environmental impacts of a product system across its entire life cycle is evaluated by using Life Cycle Assessment in accordance with the ISO 14040/14044 standards. LCA is particularly suitable for evaluating CO₂ emissions in e-grocery network design because it provides a holistic framework that accounts for emissions across all stages of the distribution system. Additionally, CO₂ emissions are assessed by collecting life cycle inventory data of both input and output flows which are converted into ecological impacts using an impact assessment method.

A concise explanation about the ReCiPe impact assessment methodology has been provided by (Goedkoop et al., 2009). Accordingly, it is regarded as a widely used approach for Life Cycle Impact Assessment (LCIA). This framework facilitates evaluation of environmental impacts at an intermediate stage in the cause effect chain (which is also known as midpoint level), as well as at the final stage where ultimate

damage to areas of protection such as human health, ecosystems, or resource availability occurs (which is also known as endpoint level). Midpoint indicators often include climate change potential in CO₂-equivalents, acidification potential in SO₂-equivalents etc. which focus on specific environmental problems, whereas endpoint indicators focus on species loss, or increased resource extraction cost etc. Based on this technique, 18 such midpoint categories are integrated with three endpoint categories; damage to human health, ecosystem diversity and resource availability in assessing the environmental impact (Goedkoop et al., 2009). In this particular research study, the primary focus was on global warming potential.

In the aspect of ecological impact assessment, the ReCiPe impact assessment step in LCA methodology plays a significant role due to several reasons. Since this approach allows harmonization of mid and end point levels (Dekker et al., 2020), analysts acquire the freedom of choosing between scientifically robust midpoint indicators and policy-relevant endpoint indicators so that the results arising from the analysis would be both credible and practical. Moreover, since this technique addresses emissions-based and resource-based impacts, researchers are facilitated in obtaining a holistic view of environmental performance. It also supports decision-making processes, as mentioned above, due to the integration of endpoint indicators into areas of protection, so that stakeholders and policymakers are better informed. Other than those, it is stated that the ReCiPe method also incorporates three cultural perspectives; individualist, hierarchist, and egalitarian, which allows exploring uncertainties and various assumptions, paving way for more flexibility in analyzing different scenarios (Rashedi & Khanam, 2020). Therefore, based on the high suitability of this approach in assessing the life cycle impacts, the technique was selected by the author.

In the context of this present study, it is important to consider how ReCiPe approach is useful in network design, particularly in E-grocery distribution systems. The technique makes use of its midpoint categories to evaluate the energy use as well as

emissions related to logistics and integrates them with ultimate damages to health and ecosystems. Thus, this plays a crucial role in quantifying ecological burdens on the network designs. Moreover, making comparisons between different network settings such as centralized, decentralized or hybrid, is facilitated by the ReCiPe method by translating emissions and resource use into measurable environmental impacts so that valid and concise decisions can be made regarding the least impactful network system on the environment. Additionally, this method allows the inclusion of resource depletion indicators which supports the identification of low carbon and resource efficient strategies. This paves way for sustainable decisions about vehicle technology, packaging materials and energy sources. Other than that, through its mid and end point levels, both global and regional effects are accounted for so that a balanced assessment on sustainability goals can be carried out locally as well as globally. Therefore, ReCiPe is not only a robust LCIA method but also a critical decision support tool for designing sustainable logistics networks that minimize environmental damage while meeting operational requirements. The aforementioned points also supported the author's decision in selecting this approach as the best suited for the present research.

When considering the assumptions with regard to all these three delivery network types, several assumptions regarding demand uniformity, packaging standardization, and exclusion of rebound effects such as increased frequency of orders due to high convenience were noticed which represent common methodological limitations that may lead to underestimation of real environmental impacts. In the centralized approach, the author had performed the analysis with the presumption of an average basket size being 55 items per order and the manufacturer's transport distance being 500km across all models. Moreover, the packaging was standardized to 100g of corrugated cardboard and 33g of filler materials per order (Van Loon et al., 2015). Even though such underlying presumptions help simplify the modelling process, the variability of actual E-grocery

operations may not be captured. As an example, small basket sizes and short supply distances; two instances commonly noticed within urban areas, may significantly lower per item emission but large and more fragmented deliveries may indicate a completely opposite effect. Also, average data had been taken into the analysis in the centralized approach rather than real-time data which may mask the seasonal demand fluctuations, traffic conditions, or delivery failures. These may lead to erroneous route efficiencies and carbon outputs. Other than that, potential rebound effects of the consumers had also been excluded from consideration which may lead to an underestimation of the true environmental footprint of centralized systems.

In the decentralized approach also, several assumptions had been made. Assuming a uniform income distribution across all blocks (Yang et al., 2024) overlooks the inconsistencies in the socioeconomic statuses that can be identified as the key driving factor of purchasing behavior and delivery density. Moreover, the model had assumed that split deliveries are restricted which removes the possibility of efficiency gains or losses brought on by partial order fulfillment, especially during times of high demand. The assumption that New York City's parcel generation reflects the national average (Li & Shih, 2024b) may also misinterpret the results since, in contrast to suburban or rural settings, high-density metropolitan environments frequently have notably different ordering patterns. Additionally, the model had presumed that all node locations and demand values within the system are known (Shi et al., 2022), a situation rarely met in reality where there are demand uncertainties and logistical constraints that may hinder operational efficiency.

The hybrid approach's scenarios were limited by strong assumptions, such as constant demand density, single package deliveries, fully charged vehicles at depots, and omission of end-of-life environmental impacts (Lemardelé et al., 2023), even though it offered potential emission savings, especially through lower energy consumption in electric fleets. Furthermore, generalizability may be restricted here since single city case studies and the Monte Carlo allocation approach may not adequately account for

the logistical and geographic heterogeneity of bigger markets, they may restrict generalizability (Ghazal et al., 2025).

Therefore, it can be understood that this overall comparative analysis is highly sensitive to the assumptions underpinning the analysis. Implementing these suggestions in the practical world would ask for more variability, geographic heterogeneity, restrictions in infrastructure and uncertainties in operations which may significantly alter the sustainability outcomes observed in the reviewed literature. Consequently, a more comprehensive assessment would offer a more precise foundation for comparisons of sustainability. All of these observations suggest that in order to fully capture the range of environmental implications, network structure should not be studied alone but rather in conjunction with vehicle technology, delivery density, and routing strategy.

4.1.2. Environmental Impact Metrics and Assessment Methods in Last Mile

Infrastructure

In this section, the author attempts to shed some light on the impact of last-mile infrastructure on the environmental performance of E-grocery. Here, the analysis revealed that the aforementioned performance is considerably affected by factors such as the delivery method, type of vehicle, geographic context, and operational assumptions.

While home delivery remains the most prevalent E-grocery mode in the global context, high emission levels were noticed in fossil-fuel-based LCVs, especially over long delivery distances (Marcucci et al., 2021). But, as mentioned in the previous section as well, route consolidation and utilization of the vehicles in an efficient manner have shown potential in managing the environmental footprint. The analysis also revealed that with regard to lowering GHG emissions and air pollutants, home delivery outsmarts other alternatives such as click-and-collect with regard to hydrocarbons and carbon monoxide emissions.

When considering click and collect (also known as click and pick), a mixed environmental profile was observed. Being a less prevalent last-mile solution, this approach indicates possibilities in reducing the delivery distances and operational time particularly in areas where there is a high customer density and facilitative urban infrastructure. But, at the same time, this model results in increased emissions when customers travel individually by car to collect their orders, as been demonstrated by Schnieder et al., 2023. Therefore, it can be inferred that it is crucial to combine these systems with infrastructure for active mobility or public transportation in order to fully achieve the potential environmental advantages.

As demonstrated in the results section, parcel lockers demonstrate significant potential for emission reductions, particularly when paired with electric vehicle fleets or strategically located to minimize customer travel (Dayal et al., 2025). Geographic distribution, however, affects how successful these systems are, since some studies indicate that coverage gaps in rural and low-density regions might reduce their total influence and ineffective locker location can negate efficiency improvements.

Consequently, crowdsourcing delivery also emerges as a promising complement to conventional logistics networks that offers reductions in both GHG emissions and local air pollutants, while also alleviating urban congestion (Alejandra Maldonado Bonilla et al., 2024). The success of this approach depends on operational coordination, load factors, and integration with low-emission transport modes. Similarly, unattended home delivery may reduce failed delivery rates and associated emissions, but the benefit depends on technological reliability and customer adoption rates.

With regard to the estimation of environmental benefits arising from low air pollutant emissions, COPERT 5.1.1 model (COmputer Programme to calculate Emission from Road Traffic) is of utmost importance. This is a standardized software tool implemented using Python language (Ali et al., 2021) developed by the European Environment Agency (EEA) with the purpose of measuring emissions resulted during road transportation. This provides the analysts with detailed projections related to

GHGs including CO₂, CH₄, N₂O, and key air pollutants like NO_x, particulate matter (PM), and CO. In addition, this approach produces accurate and consistent emission details by utilizing emission factors in combination with vehicle activity data such as vehicle type, engine size, fuel type, speed, and driving conditions. Therefore, this technique is reputable for its usage in national and regional emission reports directed to United Nations Framework Convention on Climate Change (UNFCCC) along with European Union (EU) air quality directives (Ekström et al., 2004).

This method is especially important in logistic-related ecological evaluations mainly due to being an internationally recognized standardized technique which ensures consistent and reliable data reporting relating to emissions. This data is crucial in policy and decision making procedures which aim at developing strategies to reduce emissions. It not only accounts for gases relevant for climate changes but also takes air quality pollutants into consideration so that a broad picture on transport effects can be covered (Kousoulidou et al., 2010). Moreover, as mentioned above, by modelling for different vehicle technologies, driving conditions, and fuel types, the approach allows for flexibility which is beneficial in forecasting and long-term planning.

In E-grocery logistics, last-mile delivery significantly influences the overall environmental footprint of the supply chain, and also last mile delivery is heavily depend on different road vehicle types and conditions because of this reason COPERT is highly relevant in this context. In E-grocery logistics, last-mile delivery significantly influences the overall environmental footprint of the supply chain. E-grocery operations often involve different types of vehicles under different driving conditions, urban being the most widely used one. All the variations arising from speed, stop-and-go driving and load effects can be accounted for by the COPERT's emission factors so that emissions arising from different fleet situations can be precisely calculated. Moreover, the numerous travel distances and load factors coming under different delivery strategies of the E-grocery distribution system are all accounted for by this method so that decisions and analysis is made possible on the

most suitable distribution model. Other than that, due to its ability to simulate alternative methods such as the usage of electric vehicles, eco-friendly driving and derive emission reductions, green logistics is also supported by this technique. Therefore, to sum up, COPERT is a reliable and accurate method for calculating road transport emissions, which is essential for assessing and improving e-grocery delivery systems. It is an important part of sustainability assessments and network design methods that attempt to minimize environmental impacts since it may give scenario-based emission statistics.

In order to ensure consistency and comparability across different models, a set of assumptions and limitations had been used in the analysis of last-mile infrastructure. Here, a geographic restriction had been utilized namely China, the European Region, and the United States. This supports aligning the datasets and modelling approaches into a comparable dataset, but, at the same time, it may hinder generalizing these models to regions with different logistic infrastructure, consumer behaviors and settlement patterns. Moreover, different key operational parameters had been demonstrated that vary with the model under consideration. The average transportation distance, basket size, failed delivery rates, and the number of deliveries per stop had been used as performance indicators for home delivery (Van Loon et al., 2015) whereas an assumed number of parcels per stop had been used by parcel locker approach. This allows for emissions to be normalized but potentially overlooking differences in locker density, user accessibility, and retrieval patterns. When looking at the crowd-sourcing models, assumptions of 50% vehicle load factor in Rome, a standard parcel size of 40×30×30 cm, and same-day order fulfilment requirements had been used (Gatta et al., 2021) that help simplify those models and facilitate cross-scenario comparison. But, the variability in driver availability, route deviations, or coordination efficiency between shippers, logistics operators, and platform providers may not be captured by those assumptions.

As mentioned above, even though these assumptions enable comparing between last-mile infrastructure options, capturing the real-world complexities such as seasonal demand fluctuations, urban–rural differences, or behavioral variations in consumer collection and delivery preferences may not be grasped. Therefore, the author suggests that the results should be interpreted based on the context, rather than presenting them as universally representative.

4.1.3. Environmental Impact Metrics Based on Packaging

When considering the most crucial drivers of the ecological footprint of the E-grocery system in terms of both the packaging material and its end-of-life pathway, packaging of the goods transported within this system represents a noteworthy factor. This is mainly due to the strong influence those two factors have on the overall carbon emissions. E-grocery, in contrast to traditional purchasing, may require additional packaging due to the needs of product protection against damages and contaminations, and for temperature control (for specific product types) during the delivery. This may in turn lead to high consumption of packaging materials which would result in increased resource usage and emissions. Moreover, attention should not only be paid to the production stage of them. Extra packaging may result in additional transportation impacts due to increased weight and volume, and end-of-life waste management challenges could be associated with some packaging types, particularly single-use ones (Foresti et al., 2023). All these should be taken into account in order to derive a complete assessment of E-grocery sustainability. Other than that, inclusion of packaging into this assessment enables the relevant entities to identify hotspots, compare single-use and reusable solutions, and come up with measures such as biodegradable materials, lightweight designs, and compare single-use and reusable solutions. Therefore, it can be understood that packaging plays a remarkable role in the aspect of E-grocery.

As depicted in the results section, conventional plastics and polyester can be identified as the most emission-intensive options among the packaging materials, whereas

materials including cardboard and certain low-impact plastics exhibit a relatively better performance in terms of environmental friendliness (Gonzalez-R et al., 2024) (Jiang et al., 2023). But, attention should be paid not only to the emissions resulting in the process of material production but also in how packaging is managed throughout its lifecycle. Reusable packaging, for example as been given in the results, indicate a high break-even point in this regard, converting to being environmentally friendly only after a few use cycles. This signifies the importance of designing circulation systems that amplify reuse efficiency.

Moreover, innovative approaches such as lightweight packaging or the use of recycled materials also point at how the design of the packaging materials may directly affect the reductions in both production-related emissions and downstream the transportation impacts. In the results demonstrated by (Escursell et al., 2021), lightweight options may lower the load weight which would lead to reductions in vehicle fuel consumption, paving way to lowered delivery emissions. This is particularly note-worthy in high-volume E-grocery operations. Other than that, recycled cardboard and other circular materials may contribute not only to emission reductions but also to broader resource savings, including energy and water.

Notable is also the methodological approach used in research on intra-city distribution systems as indicated by (Kang et al., 2020). These evaluations offer a more detailed and situation-specific knowledge of how packaging contributes to overall logistics emissions by combining delivery distance, features of the package distributed, and carbon emission parameters into a systematic model. Given the variety of product types, different delivery distances, and intricate combination of means of transportation found in E-grocery systems, this modeling technique is especially pertinent. It emphasizes that packaging is an active variable influencing the supply chain's overall carbon footprint rather than just a passive one.

Ultimately, these findings emphasize the need for E-grocery retailers and logistics providers to consider packaging not only as a functional requirement but as a strategic

lever for sustainability. Through deliberate material choices, investment in reuse infrastructure, and integration with optimized delivery systems, packaging can shift from being a major contributor to emissions toward becoming an enabler of greener distribution models.

4.2. Transport Operations

4.2.1. Environmental Impact Metrics and Assessment Methods Based on Vehicle

The comparative evaluation of the vehicle types point out how much of an influence imposed on the environmental performance of the E-grocery distribution system by the fleet composition. ICE vehicles, particularly diesel trucks and vans, continue to be the leading option in many regions, though their emission profiles differ significantly based on geography, vehicle type, and operational practices. Diesel-based last-mile transport is carbon intensive, as indicated by the findings section, which also shows the numbers given by other research. This underscores the need for sustainable alternatives. Furthermore, the difference in CO₂ emissions across North America, Europe, and Asia suggests that the ecological footprint is influenced by fuel efficiency regulations, vehicle maintenance, and urban infrastructure. As an example, the urban delivery fleets in specific European countries indicate comparatively low per-kilometer emissions, while those values are high in countries like United States and Latin America. All these point out that local conditions and regulatory frameworks have a direct impact on the environmental performance of the last-mile delivery systems of E-grocery distribution (Temporelli et al., 2022)(Eliyan et al., 2021). As mentioned above, though ICE vehicles demonstrate a high utilization within the scope of E-grocery, alternatives such as electric vehicles and drones show favorable potential to substantially reduce emissions in last-mile delivery. Specially, only a fraction of those emissions from conventional trucks are occurred by drones which can be used for lightweight and time-sensitive deliveries, but their usage is still

restricted due to implications regarding payload, energy demands and regulations (Ghazal et al., 2025). Similarly, quantifiable carbon reductions can also be achieved by the switching towards electric vans and trucks, although the net advantages may depend heavily on the carbon intensity of regional electricity grids.

From the standpoint of E-grocery, where delivery volume and frequency are high, the type of vehicle selected becomes a critical determinant of the distribution network's sustainability. While progressive adoption of cleaner technology might dramatically reduce the carbon footprint of urban food delivery, relying exclusively on diesel fleets runs the danger of locking the system into permanently high emissions. In the end, this comparison supports the claim that improving fleet structure is a crucial tactic for promoting environmental sustainability in E-grocery logistics, in addition to being an issue of operational efficiency.

The MEET (Methodology for calculating transportation emissions and energy consumption) framework suggested by Montaña et al. (2022b) emphasizes the methodological precision used to measure the emissions arising from E-grocery distribution vehicles. The MEET model uses a speed dependent regression technique, which takes into account vehicle attributes like curb weight and payload capacity, in contrast to raw fuel consumption statistics. The approach utilizes standardized test conditions such as flat road gradients and unloaded states which isolate the impact of vehicle speed on emissions paving way for more consistent comparisons across different transport methods. But, this suggestion also comes with disadvantages by removing the real world driving complications like changeable road gradients, stop and go urban traffic, and fluctuating payload weights prevalent in e-grocery logistics. However, when determining the actual environmental impact of vehicle choice in last-mile e-grocery delivery, the framework offers a solid baseline for assessing emissions intensity, and its conclusions highlight the significance of incorporating operational factors like load optimization, delivery density, and route planning.

Both MEET and COPERT are widely used approaches to estimate vehicle emissions, but their applications and strengths are different. MEET is more often used in theoretical and optimization driven vehicle routing problems studies due to its simplified emission formulations, while COPERT provides more empirically grounded and detailed estimates, making it especially suitable for real-world delivery vehicle emission assessments (Demir et al., 2014).

The many ways that carbon emissions might be produced during last-mile grocery delivery are effectively captured by the emission model put out by Ekren et al. (2024a). It takes into account the impact of utilizing intermediate or furthest depots, the additional journeys made by customers using their own automobiles, and the contribution of delivery vans. This model structure represents the fact that delivery emissions rely not just on van utilization but also on logistical decisions like depot allocation and consumer behavior like making additional shopping excursions. This makes the technique more realistic and appropriate for optimization studies by offering a more comprehensive view of basket-level emissions. Moreover, results from Temporelli et al. (2022b) and (Ghazal et al., 2025) show the sharp variations in energy consumption and environmental effect when comparing various delivery mechanisms. E-cargo bikes, for example, are the most energy-efficient choice since they use a fraction of the energy needed by electric trucks or vans. The potential of cargo bikes to decarbonize urban delivery, particularly in densely populated regions, is highlighted by their significantly lower CO₂ emissions. The next best choice is an electric van, which uses more energy and resources than cargo bikes but has lower emissions than a regular or hybrid van. Despite being cleaner than diesel, plug-in hybrid vans are still not as popular because of their comparatively high emissions in a number of categories.

Additionally, the research highlight other environmental indicators in addition to carbon emissions. Electric vehicles, for instance, are cleaner in terms of direct emissions, but they place a greater demand on essential materials which is a

significant trade-off when taking life cycle sustainability into account. This is demonstrated by the study of NMVOC equivalents (related to ozone production) and mineral resource consumption. Once more, cargo bikes are notable for their reduced emissions and low resource usage, highlighting their viability as a sustainable substitute for short-distance city deliveries. Other than that, Temporelli et al. (2022b) provided insight into non-exhaust particle emissions, which are a neglected yet significant aspect of vehicle sustainability. Regardless of fuel type, road, tire, and brake wear all contribute considerably to air pollution. It is interesting to note that even though electric cars lower exhaust emissions, this issue still exists. Their heavier weight can also exacerbate tire and road wear. However, as seen by the reduced scaling factor (0.2), the regenerative braking system in electric vehicles significantly decreases brake wear. This subtlety emphasizes that although EVs reduce certain pollution sources, they may exacerbate others, underscoring the significance of taking the environment's whole effect into account rather than just tailpipe emissions.

4.2.2. Environmental Impact Metrics based on Delivery Time

As been shown in the results section, the Chinese case study shows how delivery departure times may have a significant impact on travel efficiency and environmental results. The study found significant reductions in the total distance traveled and related emissions by strategically moving deliveries away from periods of high traffic. This implies that the carbon footprint of urban logistics is significantly shaped by traffic congestion. Due to delays and rerouting, cars that drive during peak traffic hours not only go farther but also use more fuel and produce more pollutants per kilometer. On the other hand, deliveries planned for noon benefited from less traffic, which allowed for shorter routes and less idle time, both of which reduced carbon emissions. Moreover, From an operational standpoint, the results demonstrate that departure time optimization is a practical approach to reducing emissions rather than just a convenience issue. Crucially, the savings attained by optimizing departure times is equivalent to the advantages of other interventions, such combining

shipments or utilizing different delivery methods. This lends credence to the idea that logistics optimization may significantly benefit the environment without requiring significant financial outlays or sophisticated technological advancements. These findings show that in order to balance sustainability goals with service quality, policymakers and practitioners must integrate traffic pattern research into last-mile delivery planning.

4.3. Product Specific Logistics

4.3.1. Environmental Impact Metrics and Assessment Methods in Cold Chain

Logistics

In product-specific logistics, specially for temperature-sensitive goods such as fresh produce including fruits and vegetables, dairy, meat, and frozen products within E-grocery operations, carbon emissions arise from two main sources. This includes fuel consumption that is utilized for both transportation and temperature control, along with electricity usage at distribution centers (DCs) (Shi et al., 2022). It is understandable that cold chain logistics is inherently more energy-intensive than normal E-grocery logistics due to the need for continuous refrigeration during storage as well as in the transit. Therefore, taking the above mentioned factors into consideration when assessing the environmental impact is crucial.

Shi et al., 2022 further proposes an equation (11) mentioned in the results to measure the overall carbon emissions of a cold chain logistics scheduling system over a defined period. Accordingly, it is highlighted that the operational network design which includes the number and location of DCs, vehicle routing, and delivery scheduling has the potential of directly influencing the emissions. Moreover, temperature control requirements is also another factor that needs to be focused on that also has an impact on emissions. Therefore, carbon emissions can be significantly lowered by efforts made to optimize these parameters such as reducing unnecessary travel distances, consolidating temperature-sensitive orders, and improving DC energy efficiency. This

agrees with the previous studies carried out on the matter, as an example, by (Teng, 2021) whose research demonstrated that route optimization in China's cold chain logistics reduced emissions from 476 kg to 413 kg CO₂. This highlights the potential of such strategies to improve environmental sustainability while maintaining product integrity particularly in products that require strict temperature control in E-grocery.

4.4. Operational and Technological Strategies

4.4.1. Optimization Approach

In E-grocery logistics, optimization is regarded as vital due to its high influence on cost efficiency, service quality and above all, environmental sustainability. But, optimizing the delivery network faces numerous hurdles with the ever-changing demand, constraints on the perishable products, narrow delivery time windows, and high last-mile delivery costs. But overcoming these challenges may enable achieving low operational costs, carbon emissions and high customer satisfaction.

In the field of E-grocery, optimization encompasses the systematic designing of a variety of tasks including delivery routes, networks, inventory flows, and time windows which all aim to achieve a balance between cost, service level and environmental impact. For this, numerous techniques can be implemented such as conventional mathematical models like Mixed Integer Linear Programming (MILP) and recent advanced approaches like metaheuristics, game theory, and machine learning-based algorithms (Clement & Spinler, 2025). These techniques address different aspects of the delivery systems such as fluctuations in demand, traffic conditions and product-specific handling requirements which pave way for more reliable, efficient and environmentally- friendly delivery systems.

As mentioned above, among the strategies for optimization, MILP has exhibited a significant potential in reducing the environmental footprint of the E-grocery distribution networks. Even according to the studies carried out previously regarding

this field, MILP-based network design and routing has demonstrated noticeable reductions in carbon emissions, which perfectly agrees with the results of the current study. As an example, the delivery routes were restructured by designating clustered districts as sink locations which paved way for 35.5% emission reductions in the Walloon region of Belgium (Arevalo-Ascanio et al., 2025). Similar kind of results could be observed in Monza, Italy where quite high reductions such as 93.8% could be achieved by integrating environmental objectives into MILP optimization. Here, emissions could be reduced up to 379.92 kg CO₂-eq per year compared to the cost-only model (Tudisco et al., 2025), indicating the importance and potential of this method in ensuring environmental sustainability. Moreover, these values highlight the practical impact of optimization in E-grocery logistics, showing that even in complex delivery networks, well-structured routing can drastically improve sustainability outcomes without compromising service.

5. Conclusion

This study aims to identify effective methods for measuring environmental impacts and comparing the environmental impacts of e-grocery distribution networks across different delivery models and operational practices. After analyzing 178 reviewed articles, the research categorized findings under logistics infrastructure, transport operations, product-specific logistics, and operational and technological strategies. This categorization provided conceptual clarity and illustrated how network design, vehicle technology, packaging, cold chain logistics, and optimization approaches collectively influence sustainability outcomes.

The analysis has shown that centralized, decentralized, and hybrid network structures each have conflicting goals. Centralized systems benefit from economies of scale but can suffer from high emissions per item without efficient routing and low carbon fleets. Decentralized networks reduce delivery distances but risk higher overall emissions during peak demand. While hybrid models are promising because they combine centralized systems with local flexibility, they require careful consideration of the impacts on vehicle efficiency, emissions, and infrastructure expansion.

In last-mile infrastructure, solutions such as parcel lockers, crowdsourcing platforms, and unattended deliveries showed significant potential to reduce emissions, though their success depends on geographic and behavioral contexts. Packaging materials proved to be a decisive factor in ecological impacts, and reusable, lightweight, and recycled materials can significantly reduce environmental impact when supported by a circular infrastructure. The choice of vehicle strongly determines the carbon footprint of operations, with electric vans, cargo bikes, and drones offering significant advantages over conventional fleets, although trade-offs remain in terms of material demand and regulatory feasibility. Optimization approaches such as MILP, metaheuristics, and machine learning show some of the most promising emission

reduction, indicating that advanced decision support systems are indispensable for sustainable e-grocery logistics.

Considering delivery departure times can significantly reduce total travel distance and improve environmental performance. The findings identified 12:30 PM as the most suitable departure time, emphasizing the potential of time-based scheduling to enhance both operational efficiency and sustainability in distribution networks.

Overall, this study highlights that environmental sustainability in e-grocery distribution is not dependent on any single factor but emerges from the combination of network design, technological aspects, operational practices, and contextual conditions. Holistic measurement approaches, such as Life Cycle Assessment (LCA) with ReCiPe, and emissions models such as COPERT and MEET, are essential for accurately quantifying impacts and guiding decisions.

Limitations

Despite providing meaningful insights, the study is subject to several limitations. The analysis is highly sensitive to the assumptions used in the reviewed literature, including average basket sizes, standardized packaging weights, constant demand density, and uniform socioeconomic distributions. These assumptions simplify modeling but in most of cases may not capture real-world variability such as seasonal demand fluctuations, traffic congestion, fragmented deliveries, or consumer rebound effects, leading to possible under or overestimation of environmental impacts.

Geographic restrictions also limit generalizability, as many studies are concentrated in regions such as the United States, China, and Europe, where logistics infrastructure and consumer behaviors differ substantially from other global markets. Case study based analyses, particularly those conducted in single cities, further reduce the applicability of findings to larger, more diverse contexts.

Moreover, several approaches excluded end-of-life impacts of vehicles and packaging, as well as broader rebound effects like increased order frequency due to convenience.

Similarly, reliance on average or modeled data rather than real-time operational datasets may mask critical variations in routing efficiency, delivery density, and consumer behavior.

While optimization strategies demonstrated significant potential for emission reduction, most findings remain based on theoretical or simulation-based studies. Their effectiveness in practical implementation under uncertain and dynamic market conditions is yet to be validated.

There is a lack of research on e-grocery logistics for the first- and middle-mile stages. Most studies focus on last-mile delivery, rather than the first and middle miles. Transportation from suppliers to distribution centres (first mile) and from distribution centers to urban hubs, warehouses, or stores (middle mile) has not been studied as much. This could be mainly because tracking emissions in these stages is difficult due to complex supply networks, limited data, and the use of third-party logistics providers. As a result, the environmental impacts of bulk transportation, storage, and order consolidation in these phases are not well measured. Closing this research gap is important for creating a complete framework to assess the environmental footprint of e-grocery distribution networks at every stage.

References

- A.A., J., & A., O. (2022). Analytical Review of E-Commerce Business Models. *African Journal of Accounting and Financial Research*, 5(2), 48–60. <https://doi.org/10.52589/ajaf-r-kmx6o2wv>
- Adolph, R. (2016). Innovative strategy in e-grocery: The future of retail outlets? *Journal of Information Technology Teaching Cases*, 14(2), 1–23.
- Agoo, J., Lanuza, R. J., Lee, J., Rivera, P. A., Velasco, N. O., Guillermo, M., & Fernando, A. (2025). Geographic Information System-Based Framework for Sustainable Small and Medium-Sized Enterprise Logistics Operations. *ISPRS International Journal of Geo-Information*, 14(1). <https://doi.org/10.3390/ijgi14010001>
- Alejandra Maldonado Bonilla, M., Bouzon, M., & Cecilia Peña-Montoya, C. (2024). Taxonomy of key practices for a sustainable Last-Mile logistics network in E-Retail: A comprehensive literature review. *Cleaner Logistics and Supply Chain*, 11(March). <https://doi.org/10.1016/j.clscn.2024.100149>
- Alharbi, A., & Stevenson, M. (2020). Refining Boolean queries to identify relevant studies for systematic review updates. *Journal of the American Medical Informatics Association*, 27(11), 1658–1666.
- Ali, M., Kamal, M. D., Tahir, A., & Atif, S. (2021). Fuel consumption monitoring through copert model—a case study for urban sustainability. *Sustainability (Switzerland)*, 13(21). <https://doi.org/10.3390/su132111614>
- Amaya, J., Encarnación, T., & Cantillo, V. (2025). Sustainable last mile delivery alternatives: Influencing factors and willingness to use. *Transportation Research Part D: Transport and Environment*, 139, 104574.
- Arevalo-Ascanio, R., Meyer, A. De, Gevaers, R., Guisson, R., Verbelen, G., & Dewulf, W. (2025). Collaborative distribution network design for sustainable parcel deliveries:

A strategic modelling approach. *Transportation Research Part D: Transport and Environment*, 141(February), 104667. <https://doi.org/10.1016/j.trd.2025.104667>

Aziz, S., Maltese, I., Marcucci, E., Gatta, V., Benmoussa, R., & Irhirane, E. H. (2022). Energy Consumption and Environmental Impact of E-Grocery: A Systematic Literature Review. In *Energies* (Vol. 15, Issue 19). MDPI. <https://doi.org/10.3390/en15197289>

Belavina, E., Girotra, K., & Kabra, A. (2017). Online grocery retail: Revenue models and environmental impact. *Management Science*, 63(6), 1781–1799. <https://doi.org/10.1287/mnsc.2016.2430>

Boysen, N., Fedtke, S., & Schwerdfeger, S. (2021). Last-mile delivery concepts: a survey from an operational research perspective. *OR Spectrum*, 43(1). Springer Berlin Heidelberg. <https://doi.org/10.1007/s00291-020-00607-8>

Brown, J. R., & Guiffrida, A. L. (2014). Carbon emissions comparison of last mile delivery versus customer pickup. *International Journal of Logistics Research and Applications*, 17(6), 503–521. <https://doi.org/10.1080/13675567.2014.907397>

Büttgen, A., Turan, B., & Hemmelmayr, V. (2021). Evaluating distribution costs and co2-emissions of a two-stage distribution system with cargo bikes: A case study in the city of innsbruck. *Sustainability (Switzerland)*, 13(24). <https://doi.org/10.3390/su132413974>

Cagliano, A. C., De Marco, A., & Rafele, C. (2017). E-grocery supply chain **management** enabled by mobile tools. *Business Process Management Journal*, 23(1), 47–70. <https://doi.org/10.1108/BPMJ-01-2016-0002>

Cano, J. A., Londoño-Pineda, A., & Rodas, C. (2022). Sustainable Logistics for E-Commerce: A Literature Review and Bibliometric Analysis. In *Sustainability (Switzerland)* (Vol. 14, Issue 19). MDPI. <https://doi.org/10.3390/su141912247>

- Chen, W., Gong, Y., Hu, X., & Zhang, Z. (2025). Green robotic warehouses: analysis of **carbon** emissions in a rack-climbing robotic warehouse. *International Journal of Production Research*, 7543. <https://doi.org/10.1080/00207543.2025.2464170>
- Clement, L., & Spinler, S. (2025). Advancing sustainability in e-commerce **packaging**: A simulation-based study for managing returnable transport items. *Transportation Research Part E: Logistics and Transportation Review*, 193(October 2024), 103868. <https://doi.org/10.1016/j.tre.2024.103868>
- Dayal, E., Unnikrishnan, A., Pani, A., & Lakshay. (2025). Optimal Location and Capacity Planning for Parcel Lockers: A Bi-Level Optimization Model Considering Planners' and Customers' Perspectives. *Transportation Research Record*. <https://doi.org/10.1177/03611981241311564>
- de Magalhães, D. J. A. V. (2021). Analysis of critical factors affecting the final **decision**-making for online grocery shopping. *Research in Transportation Economics*, 87, 101088.
- Dekker, E., Zijp, M. C., van de Kamp, M. E., Temme, E. H. M., & van Zelm, R. (2020). A taste of the new ReCiPe for life cycle assessment: consequences of the updated impact assessment method on food product LCAs. *International Journal of Life Cycle Assessment*, 25(12), 2315–2324. <https://doi.org/10.1007/s11367-019-01653-3>
- Denyer, D., & Tranfield, D. (2009). Producing a systematic review. In *The SAGE Handbook of Organizational Research Methods*, 671–689.
- Ekren, B. Y., Perotti, S., Foresti, L., & Prataviera, L. (2024). Enhancing e-grocery order fulfillment: improving product availability, cost, and emissions in last-mile delivery. *Electronic Commerce Research*. <https://doi.org/10.1007/s10660-023-09799-x>
- Ekström, M., Sjödin, Å., & Andreasson, K. (2004). Evaluation of the COPERT III emission model with on-road optical remote sensing measurements. *Atmospheric Environment*, 38(38), 6631–6641. <https://doi.org/10.1016/j.atmosenv.2004.07.019>

- Eliyan, A., Elomri, A., & Kerbache, L. (2021). The last-mile delivery challenge: evaluating the efficiency of smart parcel stations. *Supply Chain Forum*, 22(4), 360–369. <https://doi.org/10.1080/16258312.2021.1918532>
- Escursell, S., Llorach-Massana, P., & Roncero, M. B. (2021). Sustainability in e-commerce packaging: A review. *Journal of Cleaner Production*, 280, 124314. <https://doi.org/10.1016/j.jclepro.2020.124314>
- Foresti, L., Perotti, S., Ekren, B. Y., & Prativiera, L. B. (2023). E-Grocery Challenges and a Solution Approach from Multi-objective Perspectives. *Industrial Engineering in the Covid-19 Era*, 10–21.
- Galka, V., Marcucci, E., Maltese, I., Iannaccone, G., & Fan, J. (2021). E-groceries: A channel choice analysis in Shanghai. *Sustainability (Switzerland)*, 13(7), 1–18. <https://doi.org/10.3390/su13073625>
- Galkin, A., Švadlenka, L., Vrba, R., & Oliveira, L. K. de. (2025). Evaluation of cargo bike program for parcel deliveries in a medium-sized city. *Transportation Research Part D: Transport and Environment*, 140(January). <https://doi.org/10.1016/j.trd.2025.104609>
- Gatta, V., Marcucci, E., Maltese, I., Iannaccone, G., & Fan, J. (2021). E-groceries: A channel choice analysis in shanghai. *Sustainability (Switzerland)*, 13(7). <https://doi.org/10.3390/su13073625>
- Ghazal, A., Narayanan, S., Adeniran, I. O., Kehrt, C., & Antoniou, C. (2025). Analysis of logistics measures of CEP service providers for the last-mile delivery in small- and medium-sized cities: A case study for the Aachen city region. *European Transport Research Review*, 17(1). <https://doi.org/10.1186/s12544-025-00706-z>
- Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., & Zelm, R. Van. (2009). *ReCiPe_main_report_final_27-02-2009_web.pdf*. *ReCiPe 2008*, 1–44. <http://www.pre->

sustainability.com/download/misc/ReCiPe_main_report_final_27-02-2009_web.pdf

- González Romero, I., Buldeo Rai, H., Ortiz Bas, Á., & Prado Prado, J. C. (2024a). Can reusable packaging revolutionise e-commerce? Unveiling the environmental impact through a comparative carbon footprint analysis. *Journal of Cleaner Production*, 476. <https://doi.org/10.1016/j.jclepro.2024.143738>
- Gonzalez-R, P. L., Sanchez-Wells, D., & Andrade-Pineda, J. L. (2024). A bi-criteria approach to the truck-multidrone routing problem. *Expert Systems with Applications*, 243(November 2022). <https://doi.org/10.1016/j.eswa.2023.122809>
- Hovi, I. B., & Bø, E. (2024). Unlocking the potential: How can parcel lockers drive efficiency and environmental friendliness in E-commerce? *Sustainable Futures*, 7. <https://doi.org/10.1016/j.sftr.2024.100189>
- Huang, M., & Yen, B. P. C. (2021). Association for Information Systems Driving Forces for Digital Transformation-Case Studies of Q-Commerce. *International Conference on Electronic Business (ICEB)*. <https://aisel.aisnet.org/iceb2021>
- Jiang, T., Sun, Y., & Jin, Q. (2023). The environmental, economic, and social influences of government subsidies on express delivery packaging supply chain. *Environmental Science and Pollution Research*, 30(11), 29681–29698. <https://doi.org/10.1007/s11356-022-24242-8>
- Kang, P., Song, G., Chen, D., Duan, H., & Zhong, R. (2020). Characterizing the generation and spatial patterns of carbon emissions from urban express delivery service in China. *Environmental Impact Assessment Review*, 80(November 2019), 106336. <https://doi.org/10.1016/j.eiar.2019.106336>
- Kemp, N. J., Li, L., Keoleian, G. A., Kim, H. C., Wallington, T. J., & De Kleine, R. (2022). Carbon footprint of alternative grocery shopping and transportation options from retail distribution centers to customer. *Environmental Science & Technology*, 56(16), 11798–11806.

- Kousoulidou, M., Ntziachristos, L., Gkeivanidis, S., Samaras, Z., Franco, V., & Dilara, P. (2010). Validation of the COPERT road emission inventory model with real-use data. *Emissions Inventories—Informing Emerging Issues*, 40. <https://www3.epa.gov/ttnchie1/conference/ei19/session6/dilara.pdf>
- Kundu, T., Goh, M., & Choi, T. M. (2025). Home delivery vs. out-of-home delivery: Syncretic value-based strategies for urban last-mile e-commerce logistics. *Transportation Research Part A: Policy and Practice*, 193(October 2024), 104309. <https://doi.org/10.1016/j.tra.2024.104309>
- Lai, N. Y. G., Kuah, A. T. H., Kim, C. H., & Wong, K. H. (2022). Toward sustainable express deliveries for online shopping: Reusing packaging materials through reverse logistics. *Thunderbird International Business Review*, 64(4), 351–362. <https://doi.org/10.1002/tie.22259>
- Larsen, C., & Thorstenson, A. (2008). A comparison between the order and the volume fill rate for a base-stock inventory control system under a compound renewal demand process. *Journal of the Operational Research Society*, 59(6), 798–804.
- Leloup, E., Paquay, C., Pironet, T., & Oliveira, J. F. (2024). A three-phase algorithm for the three-dimensional loading vehicle routing problem with split pickups and time windows. *European Journal of Operational Research*, 323(1), 45–61. <https://doi.org/10.1016/j.ejor.2024.12.005>
- Lemardelé, C., Pinheiro Melo, S., Cerdas, F., Herrmann, C., & Estrada, M. (2023). Life-cycle analysis of last-mile parcel delivery using autonomous delivery robots. *Transportation Research Part D: Transport and Environment*, 121(December 2022). <https://doi.org/10.1016/j.trd.2023.103842>
- Li, M. Y., & Shih, F. Y. (2024). Solving the green reverse logistics problem in e-commerce using a reinforcement learning based genetic algorithm. *Electronic Commerce Research and Applications*, 68(August), 101455. <https://doi.org/10.1016/j.elerap.2024.101455>

- Luís, A. F. S., Martins, G. M. C., Caldeira, J. M. L. P., & Soares, V. N. G. J. (2022). Smart Lockers: Approaches, Challenges and Opportunities. *International Journal of Engineering and Advanced Technology*, 11(3), 141–149. <https://doi.org/10.35940/ijeat.c3374.0211322>
- Marcucci, E., Gatta, V., Le Pira, M., Chao, T., & Li, S. (2021). Bricks or clicks? Consumer channel choice and its transport and environmental implications for the grocery market in Norway. *Cities*, 110(December 2020), 103046. <https://doi.org/10.1016/j.cities.2020.103046>
- Maxner, T., Dalla Chiara, G., & Goodchild, A. (2024). The State of Sustainable Urban Last-Mile Freight Planning in the United States. *Journal of the American Planning Association*, 91(1), 88–101. <https://doi.org/10.1080/01944363.2024.2324096>
- Montaña, L. C., Malagon-Alvarado, L., Miranda, P. A., Arboleda, M. M., Solano-Charris, E. L., & Vega-Mejía, C. A. (2022). A novel mathematical approach for the Truck-and-Drone Location-Routing Problem. *Procedia Computer Science*, 200, 1378–1391. <https://doi.org/10.1016/j.procs.2022.01.339>
- Nguyen, D. H., de Leeuw, S., & Dullaert, W. E. H. (2018). Consumer Behaviour and Order Fulfilment in Online Retailing: A Systematic Review. *International Journal of Management Reviews*, 20(2), 255–276. <https://doi.org/10.1111/ijmr.12129>
- Ponce, P., Anthony, B., Bradley, R., Xu, W., Méndez, J. I., & Molina, A. (2024). A Comprehensive Framework Integrating ML, Automation Pyramid, and KPIs for Industry 5.0. *International Conference on Innovative Intelligent Industrial Production and Logistics*, 385–409.
- Qi, W., Li, L., Liu, S., & Shen, Z. J. M. (2018). Shared mobility for last-mile delivery: Design, operational prescriptions, and environmental impact. *Manufacturing and Service Operations Management*, 20(4), 737–751. <https://doi.org/10.1287/msom.2017.0683>

- Ram, N., Ahmad, P., Toth-Peter, A., de Torres de Oliveira, R., & Acharyulu, G. V. R. K. (2024). Developing a circular economy framework for e-commerce packaging materials: A study on behavioural intentions of online consumers. *Business Strategy and the Environment*, November 2023, 982–1006. <https://doi.org/10.1002/bse.4020>
- Ranathunga, M. I. D., Wijayanayake, A. N., & Niwunhella, D. H. H. (2022). Simulation-Based Efficiency Assessment of Integrated First-Mile Pickup and Last-Mile Delivery in an E-Commerce Logistics Network. *Proceedings - International Research Conference on Smart Computing and Systems Engineering, SCSE 2022*, 246–253. <https://doi.org/10.1109/SCSE56529.2022.9905083>
- Rashedi, A., & Khanam, T. (2020). Life cycle assessment of most widely adopted solar photovoltaic energy technologies by mid-point and end-point indicators of ReCiPe method. *Environmental Science and Pollution Research*, 27(23), 29075–29090. <https://doi.org/10.1007/s11356-020-09194-1>
- Reichmuth, D. S., Lutz, A. E., Manley, D. K., & Keller, J. O. (2013). Comparison of the technical potential for hydrogen, battery electric, and conventional light-duty vehicles to reduce greenhouse gas emissions and petroleum consumption in the United States. *International Journal of Hydrogen Energy*, 38(2), 1200–1208. <https://doi.org/10.1016/j.ijhydene.2012.10.047>
- Russo, A., Tesoriere, G., Al-Rashid, M. A., & Campisi, T. (2023). Pick-Up Point Location Optimization Using a Two-Level Multi-objective Approach: The Enna Case Study. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 14106 LNCS, 309–322. https://doi.org/10.1007/978-3-031-37111-0_22
- Sahay, N., & Ierapetritou, M. (2014). Hybrid simulation based optimization framework for centralized and decentralized supply chains. *Industrial and Engineering Chemistry Research*, 53(10), 3996–4007. <https://doi.org/10.1021/ie403395p>

- Schnieder, M., Hinde, C., & West, A. (2023). Land Efficient Mobility and Emissions: Click and Collect vs. Grocery Deliveries in Switzerland. *Sustainability (Switzerland)*, 15(11). <https://doi.org/10.3390/su15118814>
- Shi, Y., Lin, Y., Lim, M. K., Tseng, M. L., Tan, C., & Li, Y. (2022). An intelligent green scheduling system for sustainable cold chain logistics. *Expert Systems with Applications*, 209(December 2021), 118378. <https://doi.org/10.1016/j.eswa.2022.118378>
- Siegfried, P., Michel, A., Tänzler, J., & Jiyuan Zhang, J. (2021). Analyzing Sustainability Issues in Urban Logistics in the Context of Growth of E-Commerce. *Journal of Social Sciences*, IV(1)(March). [https://doi.org/10.52326/jss.utm.2021.4\(1\).01](https://doi.org/10.52326/jss.utm.2021.4(1).01)
- Siragusa, C., & Tumino, A. (2022). E-grocery: comparing the environmental impacts of the online and offline purchasing processes. *International Journal of Logistics Research and Applications*, 25(8), 1164–1190. <https://doi.org/10.1080/13675567.2021.1892041>
- Suel, E., & Polak, J. W. (2017). Development of joint models for channel, store, and travel mode choice: Grocery shopping in London. *Transportation Research Part A: Policy and Practice*, 99, 147–162. <https://doi.org/10.1016/j.tra.2017.03.009>
- Temporelli, A., Brambilla, P. C., Brivio, E., & Girardi, P. (2022). Last Mile Logistics Life Cycle Assessment: A Comparative Analysis from Diesel Van to E-Cargo Bike. *Energies*, 15(20). <https://doi.org/10.3390/en15207817>
- Teng, S. (2021). Route planning method for cross-border e-commerce logistics of agricultural products based on recurrent neural network. *Soft Computing*, 25(18), 12107–12116. <https://doi.org/10.1007/s00500-021-05861-8>
- Toniolo, S., Pierli, G., Bravi, L., Liberatore, L., & Murmura, F. (2025). Digital technologies and circularity: trade-offs in the development of life cycle assessment. *International Journal of Life Cycle Assessment*, UNEP 2024. <https://doi.org/10.1007/s11367-025-02436-9>

- Trott, M., Von Viebahn, C., & Auf Der Landwehr, M. (2020). Towards A More Sustainable Future? Simulating the Environmental Impact of Online and Offline Grocery Supply Chains. *Proceedings - Winter Simulation Conference, 2020-December*, 1218–1229. <https://doi.org/10.1109/WSC48552.2020.9383987>
- Tudisco, V., Perotti, S., Ekren, B. Y., & Aktas, E. (2025). Sustainable e-grocery home delivery: An optimization model considering on-demand vehicles. *Computers and Industrial Engineering*, 201(December 2024), 110874. <https://doi.org/10.1016/j.cie.2025.110874>
- Van Loon, P., Deketele, L., Dewaele, J., McKinnon, A., & Rutherford, C. (2015). A comparative analysis of carbon emissions from online retailing of fast moving consumer goods. *Journal of Cleaner Production*, 106(2015), 478–486. <https://doi.org/10.1016/j.jclepro.2014.06.060>
- Winkelmann, D., Tolkmitt, F., Ulrich, M., & Römer, M. (2024). Integrated storage assignment for an E-grocery fulfilment centre: accounting for day-of-week demand patterns. *Flexible Services and Manufacturing Journal*, 37(2), 558–598. <https://doi.org/10.1007/s10696-024-09549-7>
- Wu, Y., Wang, B., & Huo, B. (2024). Sustainability challenges of last-mile logistics and transition to online grocery retailing in sparsely populated areas. *Industrial Management & Data Systems*, 124(12), 3197–3217.
- Yang, H., Landes, H., & Chow, J. Y. J. (2023). A large-scale analytical residential parcel delivery model evaluating greenhouse gas emissions, COVID-19 impact, and cargo bikes. *International Journal of Transportation Science and Technology*. <https://doi.org/10.1016/j.ijst.2023.08.002>
- Zhang, C., Zhang, H., Pu, T., & Pan, J. (2025). Supply Chain Demand Forecasting Based on Data Mining Algorithm and Seq2Seq. *International Journal of Control, Automation and Systems*, 23(1), 89–104.

Zissis, D., Aktas, E., & Bourlakis, M. (2018). Collaboration in urban distribution of online grocery orders. *International Journal of Logistics Management*, 29(4), 1196–1214.
<https://doi.org/10.1108/IJLM-11-2017-0303>