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Decarbonizing last-mile logistics: A life cycle and just transition perspective

Sara Toniolo [a,*], Ivan Russo [a], Jingzheng Ren [b], Md. Abdul Moktadir [b]

[a] University of Verona, Department of Management, Italy
[b] The Hong Kong Polytechnic University, Department of Industrial and Systems Engineering, Hong Kong

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ABSTRACT

Emissions from logistics and last-mile delivery represent a growing share of global greenhouse gases, fueled by e-commerce expansion and rising demand for rapid delivery. While decarbonization is essential, existing efforts largely prioritize technological and operational solutions, leaving their broader socio-environmental implications underexplored. This study conducts a systematic literature review to define what decarbonizing last-mile logistics entails and to identify the practices most frequently proposed to reduce emissions. Building on life cycle thinking as an integrative analytical lens, the analysis reveals how these practices, while reducing carbon emissions, may also generate unintended socio-ecological effects through shifting burdens across supply chain stages. To address these side effects, the review integrates the concept of a just transition, reframing decarbonization beyond efficiency and technological gains toward socially equitable and environmentally comprehensive pathways. The findings contribute by (1) mapping patterns of decarbonization practices across disciplines, (2) showing how life cycle thinking uncovers hidden side effects, and (3) advancing just transition as a conceptual and policy framework to guide last-mile logistics toward climate mitigation that is both effective and fair.

1. Introduction

Emissions from supply chain operations are, on average, 11.4 times larger than direct emissions from company operations (CDP, 2023). Understanding the distribution of these emissions across the supply chain is critical for initiating large-scale reduction efforts (Science Based Targets Initiative, 2023). Logistics activities significantly contribute to these emissions, accounting for 7 % of global greenhouse gas emissions (McKinsey and Company, 2024). Freight transport generates 8 % of global CO_2 emissions, increasing to 11 % when logistics sites are included (Smart Freight Centre, 2020). While representing only 15 % of freight activity, road freight transport accounts for 44 % of the sector's CO_2 emissions. Alarmingly, emissions from the transportation sector are projected to increase by 16 % by 2050 (ITF, 2021).

The rapid growth of e-commerce has further exacerbated emissions related to logistics. Although e-commerce has the potential to reduce emissions by minimizing individual shopping trips, its overall environmental impacts remain uncertain (Jaller et al., 2023). Without intervention, the number of delivery vehicles in major cities is expected to increase by 36 % by 2030, resulting in a 32 % rise in emissions (World Economic Forum (WEF), 2020). Reducing emissions associated with e-commerce entails managing conflicting needs and compromises (Garus et al., 2022; Jaller et al., 2021), adjusting delivery capacity, developing more sustainable solutions, integrating partners' logistic flows (Moncef and Monnet Dupuy, 2021; Cao et al., 2024) and finding a balance between the cost of mitigation and the proportion of reduced emissions (Parkinson et al., 2019; Silva and Nilsson, 2024).

As e-commerce continues to experience rapid growth, the environmental impact of its associated logistics, particularly in last-mile delivery, has become a critical concern. Recent studies highlight the need for decarbonization strategies in logistics networks to mitigate the carbon footprint of increased consumer demand (González-Romero et al., 2025).

Decarbonizing logistics and last-mile delivery means activating "actions to reduce carbon dioxide emissions" (IPCC, 2022) and facing significant scientific, societal, and environmental challenges (Ha et al., 2023). Last-mile logistics, including home delivery with vans and transport to cross-docks, accounts for nearly 43 % of the CO_2-eq emissions associated with an entire fulfillment method — including last-mile delivery, retail operations, e-fulfillment centers, manufacturer

* Corresponding author.
E-mail addresses: sara.toniolo@univr.it (S. Toniolo), ivan.russo@univr.it (I. Russo), jzhren@polyu.edu.hk (J. Ren), abdul.moktadir@connect.polyu.hk (Md.A. Moktadir).

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transportation, packaging, and ICT for product purchase (Van Loon et al., 2015). For the last mile delivery of 1 ton of parcels, a range of 33–44 kg CO_2-eq is emitted when using a diesel fleet, which can be 37 %–50 % cut down with the adoption of electric vehicles, depending on different traffic conditions, and causing a total range of 457–290 kg CO_2-eq daily (Croci et al., 2021). It has been estimated that at the supply chain level, the last-mile delivery can represent 5.3–5.8 % of CO_2-eq emissions associated with the food system of an entire city for one year (Stelwagen et al., 2021).

Successfully decarbonizing last-mile delivery requires navigating the tensions among operational efficiency, cost-effectiveness, sustainability goals (Garus et al., 2022; Moncef and Monnet Dupuy, 2021) and consumer expectations for rapid delivery (Paluzzi et al., 2025). Innovations such as autonomous delivery systems and intelligent transportation offer promise, yet their long-term environmental and societal impacts remain uncertain (Boysen et al., 2018; Sun et al., 2022). New challenges have emerged for various actors involved in last-mile delivery, including logistics service providers (Peppel and Spinler, 2022; Peppel et al., 2024), who face increasing pressure to reduce emissions associated with last-mile logistics (Suh et al., 2012; Liu et al., 2020), to reduce energy consumptions (Tian and Sarkis, 2022), manage different transportation modes (Fontaine et al., 2023) and to address the exacerbation of congestion, pollution, and social inequities linked to the rapid growth of e-commerce (Ameknassi et al., 2016; Ha et al., 2023).

Despite its importance, the knowledge about the environmental burdens of last-mile logistics is still limited, and the academic community is starting to perceive the need to extend the knowledge from a sustainability perspective (Ha et al., 2023) and, in some cases, apply a life cycle perspective as a systematic approach to those challenges (Edwards et al., 2010; Stelwagen et al., 2021). In detail, life cycle thinking offers a systematic approach to decarbonizing last-mile logistics by assessing environmental, social, and economic impacts across the entire supply chain. While innovative solutions such as drones, autonomous vehicles, or cargo bikes can mitigate emissions (Wüstenhagen et al., 2021; Assmann et al., 2020), their benefits often depend on contextual factors like energy mix, routing, packaging, and transshipment design (Chiang et al., 2019; Li et al., 2021). Similarly, service deliveries may reduce environmental impact compared to consumer shopping trips; however, outcomes vary depending on factors such as delivery density, time windows, failed deliveries, and reverse logistics (Hoehne and Chester, 2017; Stelwagen et al., 2021).

Existing research on the last-mile has largely focused on technical, economic, and planning solutions, with a limited, even if increasing, focus on environmental and social impacts (Masorgo et al., 2024). A clear definition of decarbonizing last-mile logistics remains elusive, as do standardized methodologies for measuring progress toward this goal, including identifying the boundaries and scope of the domain under investigation. Decarbonizing is essential for addressing climate change, but decarbonization alone cannot fully represent sustainability, and assessing socio-ecological burdens beyond greenhouse gas (GHG) emissions becomes crucial for evaluating transitioning strategies (Fernández-González et al., 2023; Grubert, 2021).

Furthermore, despite growing awareness, efforts to decarbonize last-mile logistics remain underexplored, particularly through the lens of a transition concept (Karaosman et al., 2024), which integrates social and economic dimensions into sustainability efforts.

Integrating the just transition approach can enhance the operational feasibility of decarbonization practices by identifying synergies between environmental goals and social objectives, such as initiating a strong social dialogue with local communities (Karaosman et al., 2024), avoiding maladaptation (Shah et al., 2024).

Promoting just transitions involves actively developing sustainable systems by supporting practices that are both less environmentally impactful and inclusive (Cigna et al., 2023), focusing on both fair phase-out of old systems and building new alternatives beyond rapid transitions without social considerations and top-down transitions excluding affected communities and workers (European Environment Agency, 2024).

This makes the just transition approach uniquely suited to addressing the complexities of last-mile logistics decarbonization, which can be viewed as a transformative adaptation to climate change (Taylor et al., 2025). This perspective is especially relevant for last-mile delivery, where decarbonization efforts frequently entail trade-offs between operational costs and delivery speed, directly impacting businesses and consumers.

To develop effective climate mitigation strategies, it is essential to evaluate potential unintended side effects, and a life cycle perspective helps assess both (Lausselet and Brattebø, 2021).

Considering the existing gaps and the necessity of understanding the last-mile decarbonization through the lens of just transition for the logistics supply chain, this research systematically reviews the existing literature to identify key themes and patterns, offering incremental insights into how last-mile delivery could embrace the transition toward decarbonized logistics by exploring existing practices (Durach et al., 2021) aimed at reducing CO_2 emissions applying life cycle thinking to reveal the unintended side effects.

By combining just transition with life cycle thinking, it is possible to achieve a systemic view of the social and environmental impacts of systems or processes. Just transition provides a framework for analyzing fairness and equity, focusing on the distribution of benefits and burdens across various stakeholders (Wang and Lo, 2021; Shah et al., 2024), while life cycle thinking tracks the entire lifespan of a system (Hellweg and Milà i Canals, 2014) and can help actual transition toward solutions adopting an integrated, comprehensive and participatory approach (Sala et al., 2015) preventing double-counting (Xiong and Xu, 2023; Bach, 2023), avoiding carbon leakage (Finkbeiner and Bach, 2021), and reducing the risk of environmental impacts shifting (Caiardi et al., 2024; Parvathy et al., 2025; Valdivia et al., 2021) or new problems (Caiardi et al., 2024). Together, they help identify side-effects overlooked when applying a single framework (Fortier et al., 2019; Le et al., 2024), also from a social perspective (van der Veen et al., 2025), including mobility scenarios (Bouillass et al., 2021).

More specifically, the research seeks to combine just transition with life cycle thinking to decarbonize last-mile logistics and to address the following research questions to achieve its research goal:

RQ1: What patterns of practices emerge across different research fields that can be applied to decarbonize last-mile logistics?
RQ2: What unintended socio-ecological side effects may arise due to last-mile decarbonization practices and through which pathways?

To further clarify the scope of this study, it is essential to define the concept of last-mile logistics, which plays a pivotal role in the logistics and environmental performance of e-commerce. In this study, the term last-mile logistics refers to "*the last stretch of a business-to-consumer (B2C) parcel delivery service. It takes place from the order penetration point to the final consignee's preferred destination point*", as defined by Lim et al. (2018). Last-mile logistics is articulated in three key processes: picking (from warehouses or stores), packing, and delivery. It begins at the location where products are stored after an order is confirmed and continues through the transportation phase from the fulfillment point to the final destination. Delivery can be carried out via three main modes: self-delivery, third-party logistics (3PL) including crowdsourcing, and consumer pickup (Lim et al., 2018).

The research aims to fill a critical gap in the literature by defining what decarbonizing last-mile logistics entails, from identifying decarbonizing practices and methodologies to measuring and guiding decarbonization efforts in line with just transition principles.

The main contributions of this review are threefold. First, by analyzing the selected studies, the review offers new insights into how last-mile logistics can support decarbonization, identifying and capturing relevant decarbonization practices. Second, through an interpretative analysis of these practices, the review introduces the application of the just transition framework, reframing decarbonization practices toward just transition. Finally, by applying a life cycle thinking perspective, the possible unintended side effects of decarbonization are revealed. As an innovative contribution, this research analyses how a just transition can ensure that decarbonization efforts in last-mile logistics do not generate unintended socio-ecological side effects and how to address them. It proposes a view of the side effects of decarbonizing last-mile logistics toward a just transition.

2. Methodology

This study builds on the conceptualization of a just transition as proposed by Karaosman et al. (2024), which aims to guide supply chain management toward decarbonization, considering the needs of nature, communities, and individuals. They propose four archetypes developed cross-referencing the purpose dimension (profit or shared outcomes) and the governance dimension (government-/industry-led or civil society-involved) of decarbonization practices along a supply chain, using cases from various industries to demonstrate the utility of distinguishing between profit-oriented and shared-outcomes models. The conceptualization of Karaosman et al. (2024) is considered appropriate for our study because it is developed for the management of supply chains, unlike other studies in the literature, which were mainly focused on policy or labor, such as Kaljonen et al. (2024) discussing policy interventions, and Wang and Lo (2021) focusing on labor-oriented.

Through the lens of a just transition, it is possible to guide practices along a supply chain toward decarbonization, aligning social and ecological needs. In this research, the just transition lens is employed to explore how to move beyond decarbonization practices toward practices of just transitioning from a supply chain view.

Based also on the previous research of Pagell and Wu (2009) and Walker et al. (2024), this study shows how decarbonization means transitioning to decarbonization practices with multidimensional thinking, combining both social and environmental dimensions, and reveals interactions between decarbonization and social issues.

To answer RQ1 and RQ2, a systematic literature review approach (Durach et al., 2017) was used to discuss the practices available to decarbonize the last-mile logistics systematically. The systematic literature review is organized into two parts. In the first part, RQ1 is addressed, extracting the main themes investigated by the selected studies and the research methods used. In this way, it is possible to identify the main decarbonization practices suggested and a combination of them, based on topics and research methods, which lead to subgroups of practices. Successively, the obtained patterns of practices are

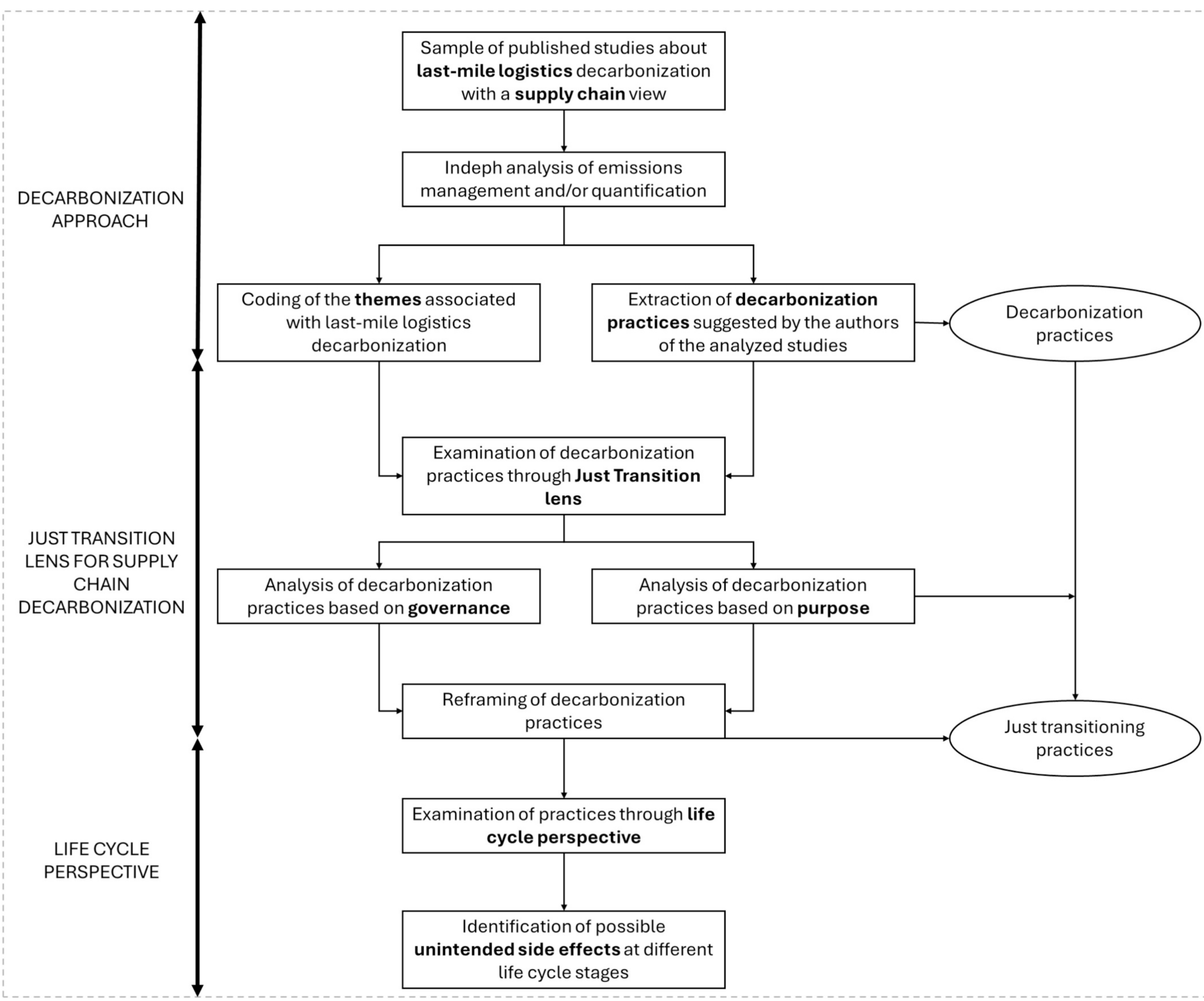

Fig. 1. The scheme of the research.

classified through the just transition approach, identifying civil society-involved practices and industry-led practices leading to economic and social-ecological improvement. The first part of the literature review analyzes how evolving decarbonization practices are transitioning toward practices (Section 3.1).

The second part, RQ2, is addressed by examining the transitioning practices through the life cycle perspective, linking them to different stages of the supply chain. This perspective, which has declined in all its social, economic, or environmental applications, highlights how decarbonization efforts can unintentionally generate new socio-ecological effects, such as reducing carbon emissions while increasing resource use, social inequities, or other environmental burdens. Doing so helps evolve decarbonization practices toward a just transition, preventing narrow improvements in one area from causing hidden trade-offs elsewhere (Section 4). Fig. 1 schematizes this research, showing that the different approaches to decarbonize the last-mile logistics can be enhanced through the just transition, providing a new combined perspective and revealing unintended side effects.

2.1.1. Required characteristics of primary studies

Since we seek to provide a pattern of practices at the intersection between last-mile logistics and decarbonization, this systematic literature review begins by considering studies regarding the emissions associated with the last-mile. According to the research questions, only studies regarding the last-mile aspects are included in this research. The unit of analysis was each scientific article published in journals, written in English, and retrieved through the selected keyword.

2.1.2. Baseline sample

A sample of potential relevant literature was retrieved to identify and analyze previous research about decarbonization and last-mile logistics. The database used was ISI Web of Knowledge, as employed by Ji et al. (2018), with the following combination of keywords: (“last mile” OR “last-mile” OR “last mile delivery” OR “last-mile delivery” OR “package delivery” OR “on-demand delivery” OR “drone delivery” OR “urban delivery” OR “parcel delivery” OR “final mile delivery” OR “final-mile delivery” OR “final mile” OR “final-mile” OR “home delivery” OR “grocery delivery” OR “urban logistics” OR “city logistics” OR “B2C distribution” OR “business-to-consumer distribution”) AND “supply chain” AND (“carbon footprint” OR emission* OR decarbon* OR “global warming” OR “climate change”), without time filtering.

Thus, including “*supply chain*” allows for a more focused, rigorous, and relevant exploration of the research topic, also mirroring the definition of last-mile logistics developed by Lim et al. (2018). Moreover, our approach to studying last-mile decarbonization is framed through a supply-chain perspective, which ensures that the selected studies are both comprehensive and closely aligned with the dynamics and challenges of emissions across supply chains.

No time period was specified for conducting this literature review to avoid excluding any relevant articles. It is noted that this literature search was performed in November 2024 and yielded an initial sample of 142 studies.

This analysis relies solely on the Web of Science database, which provides well-established and high-quality coverage of the thematic areas under investigation, along with consistent indexing standards. Using a single database avoids duplication of results and inconsistencies caused by differences in indexing criteria. Previous comparative studies have shown that, for specialized and well-covered fields such as the one analyzed here, the coverage of Web of Science is appropriate (Mongeon and Paul-Hus, 2016). This strategy, while maintaining alignment with the study's objectives, may have omitted relevant works addressing last-mile decarbonization, such as research on healthcare supply chains (Gunaratne et al., 2022) and pooling in urban logistics (Apostolopoulos and Kasselouris, 2022).

2.1.3. Synthesis sample

In the identification phase, the mentioned keywords provided 142 articles that were included in the initial sample. In the screening phase, with reference to the types, only articles and reviews were selected, excluding conference proceedings and book chapters; regarding the language, only articles written in English were included, leading to a baseline sample of 114 articles published from 2010 to 2024. Then each article was analyzed based on title and abstract. Articles that did not focus on carbon emissions or decarbonization activities and those without a supply chain perspective were excluded. Also, the articles on the health supply chain, with a strong focus on vaccine supply during COVID and blood supply, were excluded because they were considered off-topic. Only articles published in scientific journals were included. After this screening, 64 unsuitable results were eliminated based on their title and abstract, resulting in 50 studies. These were further analyzed, going beyond title and abstract, excluding the other 6 studies, and finally resulting in 44 studies. Finally, in the included phase, there is no additional study added as a single database was used, resulting in 44 studies in total for in-depth analysis (Fig. 2). The synthesis sample of 44 papers is particularly relevant as it focuses on supply chain management with a specific emphasis on emissions, addressing both the supply chain view and the decarbonization of last-mile logistics from different research fields.

2.1.4. Literature synthesis

The final 44 studies included in the analysis sample were analyzed separately to identify the main themes emerging associated with last-mile decarbonization and the employed research methods (first coding process) and the decarbonization practices (second coding process).

The first coding process was performed to extract the themes (reported in Section 3.1) and the research methods (Section 3.2). The themes were extracted through a keyword occurrence analysis to understand the range of topics present in titles and abstracts (Sharma et al., 2023). This step was performed using VOS viewer software (Van Eck and Waltman, 2010), version 1.6.20. It is worth noting that this study does not constitute a bibliometric analysis, but a systematic review, where all 44 papers were carefully read and analyzed by the authors. VOS viewer was used exclusively to assist with the classification of the literature, from which three main themes were extracted based on the most commonly occurring words in titles and abstracts, as reported in Table A1 (Appendix). The list of terms obtained from VOS viewer was refined by manually selecting the most relevant ones, based on occurrences and relevance score. Overly generic terms, such as “number” and “case study”, and those directly associated with last-mile, such as “distribution” and “vehicle” were neglected. To ensure the transparency of this selection process, Table A1 (Appendix) reports all the extracted terms, highlighting the selected ones, which are “Assessment”, “Challenge”, “Collaboration”, “Consumer”, and “Demand”. This selection was based on conceptual relevance rather than just frequency alone, thus preventing an arbitrary filtering of terms. The five terms extracted from this analysis were used to develop the input vocabulary for the linguistic and word count conducted through the Linguistic Inquiry and Word Count (LIWC) software version 22 (Pennebaker et al., 2003), which allows assigning each paper to the exact terms. This step was necessary to understand which articles used in which specific terms, as illustrated in Table A2 (Appendix), and guided the definition of the thematic groups of the studies included in the review. The most frequent words extracted through the VOS viewer and LIWC were subjected to a qualitative validation process. Each term was examined through a comprehensive reading of the corresponding full paper to ensure its representativeness of the article's core content. When the in-depth analysis indicated that a term did not accurately reflect the thematic focus of the paper, it was replaced with a more appropriate alternative, selected on the basis of the paper's principal topics. The thematic grouping was subsequently

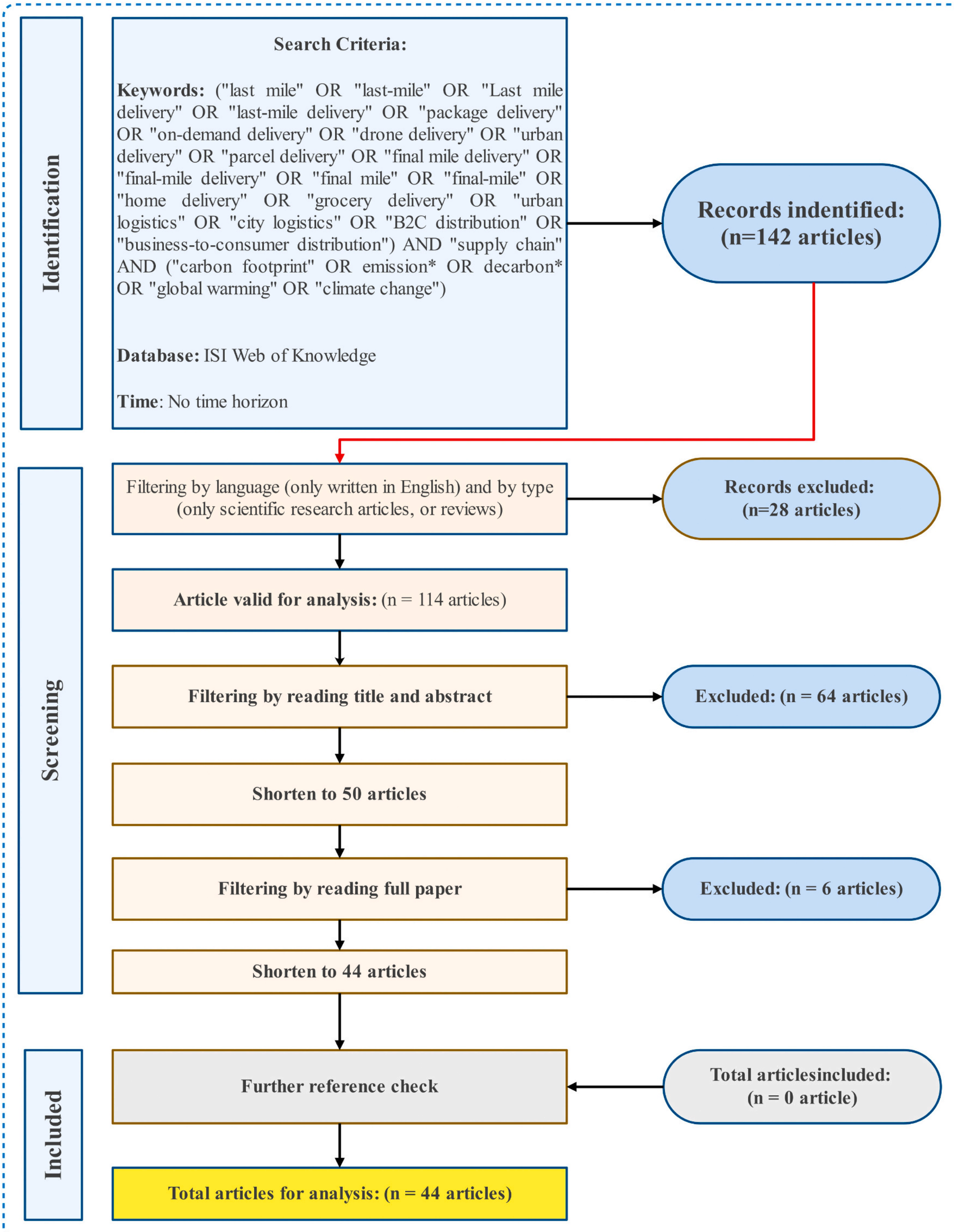

Fig. 2. Selection process of the baseline and synthesis sample.

performed using this refined and validated set of terms. The analyses performed with VOS viewer and LIWC served only as tools to group the literature for descriptive purposes. They did not determine or limit the subsequent analysis, which was conducted independently and aimed at capturing all relevant dimensions of last-mile logistics decarbonization across the reviewed studies. In this way, it was possible to identify three main themes among the different studies included in this review: “consumer attitude and behavior”, “optimization and quantification”, and “challenges and obstacles”. The methodologies were extracted by reading each paper in depth and discussing any discrepancies among the research team members.

The second coding process was conducted with the aim of capturing the different decarbonization practices suggested in the selected studies. Each study's discussion and conclusion sections were analyzed in depth, and any discrepancies were resolved through discussions among the research team.

At the end of both coding processes, the main findings were synthesized and consolidated to identify the key themes, research methodologies employed, and proposed improvement practices for decarbonizing last-mile logistics (Baldi et al., 2024). An appropriate evaluation was conducted for all included studies to evaluate their adequacy in addressing the aim of the research and answering RQ1 and RQ2. In order to conduct a meaningful evaluation, it was essential to establish specific dimensions, criteria, and a classification framework that allow for the systematic organization and comparison of findings (Toniolo et al., 2023). To ensure a systematic and transparent assessment of the reviewed studies, four dimensions were defined: rigour, contextualization, relevance, and representativeness. The rigour dimension assesses the reliability and academic quality of each source based on the ranking or peer-review status of the publication venue. This criterion guarantees that the selected contributions meet established standards of scholarly validity. The contextualization dimension evaluates whether each study explicitly specifies its geographical scope and the type of means employed to perform last-mile delivery. This criterion is essential for positioning findings within their operational and spatial contexts, allowing for meaningful comparisons across regions and applications. The relevance dimension examines the degree of methodological alignment between each study and the objectives of this research. In particular, it examines whether the methods adopted are suitable for identifying and analyzing patterns of last-mile decarbonization practices. Finally, the representativeness dimension focuses on the consistency between a paper's title and abstract, particularly in terms of extracted keywords or the most frequent terms, and its full-text content. This criterion verifies whether the terminology used accurately reflects the studies' main themes. Table A3 and Table A4 (Appendix) illustrate the criteria and the classification to evaluate the appropriateness of the included studies. All the included studies were classified as high or medium appropriate as reported in Table A5 (Appendix) and were included in the analysis.

After grouping the selected papers into three groups corresponding to the three themes revealed through the first coding ("consumer attitude and behavior", "optimization and quantification", "challenges and obstacles"), all the decarbonization practices were assigned a different archetype according to the just transition framework. To determine whether a specific practice falls under the just transition dimension, the following analytical criteria were applied. Practices were classified as government/industry-led or civil society-involved based on the identity of the leading actor, the governance mode, and the degree of participatory engagement. Government/industry-led practices were identified as those initiated, funded, or primarily managed by public authorities or private companies, typically operating through hierarchical or institutionalized decision-making structures. In contrast, civil society-involved practices were those in which non-governmental organizations, community groups, or local networks played a significant role in shaping objectives, implementation. In addition, practices were classified as either profit-oriented or shared outcomes-oriented according to their primary objectives and benefit distribution mechanisms. Profit-oriented practices were identified as those primarily aimed at generating financial returns for investors or participating firms, characterized by market-based incentives, private capital investment, and revenue-maximizing logics. Shared outcomes-oriented practices, by contrast, sought to balance economic viability with broader social or environmental objectives, emphasizing collective benefits.

In this way, for each theme, it was possible to assign the decarbonization practices to the four archetypes of just transition (Karaosman et al., 2024) to identify the practices government-/industry-led or involving civil society and profit or shared outcomes-oriented. Then, all practices associated with the three themes revealed in the first coding were summarized, eliminating duplicated practices across the different themes to give a picture of the transitioning practices based on their purposes of shared outcomes or profit. These transitioning practices were then crossed with the research method employed in the studies, building in this way the final pattern of improvement practices and giving an answer to RQ1 (Section 3.1). These final patterns of practices are a combination of profit purposes and shared outcome purposes.

The practices were further inductively grouped into 4 sub-groups representing similar activities. The 4 sub-groups of practices, both profit and shared outcomes-oriented, were analyzed to understand how they can be adapted through the just transitioning framework. The practices revealed from the literature were then interpreted to reveal possible unintended socio-ecological side effects of last-mile decarbonization to ensure a just transition (Karaosman and Marshall, 2023), enlarging the vision with a life cycle thinking approach.

For each sub-group of practices, the life cycle thinking perspective was applied, identifying the possible unintended side effects on society and the environment to be considered in order to achieve decarbonization in environmentally and socially just ways (Pagell and Wu, 2009), giving an answer to RQ2 and evolving the decarbonization practices toward just transition (Section 4).

A sensitivity analysis was conducted to examine the robustness of the review process and the consistency of the qualitative synthesis with respect to key methodological decisions. This procedure aimed to assess whether the overall interpretations would remain stable under alternative inclusion criteria or quality appraisal thresholds. Specifically, sensitivity analyses were planned to explore the potential influence of (a) the exclusion of studies rated as "medium appropriateness" with reference to the aim of our research, (b) the restriction to specific study designs applying a complete system boundary (picking, packaging, and delivery), and (c) limiting to studies of one thematic group. The purpose of this sensitivity assessment was not to test the empirical findings but to evaluate the stability of the synthesis process and to enhance the credibility and trustworthiness of the review's methodological framework.

3. Results

This research investigates the patterns of practices emerging across diverse geographical contexts and research fields aimed at decarbonizing last-mile logistics, particularly in the context of industrial and social-ecological requirements.

In terms of geographical distribution, 30 studies explicitly reported the location of the analyzed practices. Of these, 12 were set in Europe, 8 in the United States, and 3 in China, while the remaining cases were distributed across South America, Oceania, and Africa. This distribution reflects the predominance of research focusing on industrialized economies, with comparatively limited evidence from the Global South.

In Europe, last-mile logistics decarbonization solutions, revealed through the analyzed studies, focus primarily on collaboration among stakeholders and the use of advanced technologies to reduce emissions and improve operational efficiency. Cooperation between companies and with customers to reduce urban congestion and delivery costs has been explored with reference to abnormal demand (Argyropoulou et al., 2023), for freight transportation (Aloui et al., 2021), for on-demand delivery service (Labarthe et al., 2024), and with reference to consumers' influence on distribution (Sallnäs and Björklund, 2020). Specifically, there is a focus on adopting electric vehicles in place of traditional fuels to reduce GHG emission (Álvarez-Rodríguez et al., 2020). In Asia, the context is highly diverse, but the key to improving logistics operations often lies in the adoption of advanced technologies and economic profitability (Hong et al., 2022; Hu et al., 2019), addressing complex scenarios (Prajapati et al., 2021). In China, for example, crowd shipping is being experimented (Wang et al., 2024), enabling the shared distribution of costs, optimizing routes and resources. In the studies developed in the United States, last-mile logistics decarbonization combines technological aspects and consumer habits (Santiago-Montano et al., 2024; Zhao and Lee, 2023). Simulation models and emissions analyses are used to optimize deliveries using electric vehicles, such as e-trikes (Azad et al., 2023), and including consumers' purchasing habits (Lerner et al., 2024). Studies conducted in South America focus on electric cargo bikes, small urban freight delivery, and consumers' choices (Nogueira et al., 2021; de Oliveira et al., 2021). In the only study conducted in Africa (Ouhader and El Kyal, 2023), last-mile logistics focuses on route optimization and collaboration among companies. Overall, the studies included in this research, applied in different regions, highlight a mix of approaches that range from collaboration among stakeholders, such as companies and consumers, to the adoption of technologies, such as electric vehicles and autonomous vehicles. The following sections present how decarbonization can manifest in last-mile logistics across different geographical contexts. Different themes of the logistic services (Section 3.1) and research methods (Section 3.2) are also discussed from a decarbonization perspective, with the intent of identifying how decarbonization can decline in this field and how their actions translate from decarbonization practices to just transition.

This research further explores the progression from initial decarbonization practices to just transitioning to analyze the contribution of solutions beyond climate adaptation (Goodwin et al., 2024). This progression underscores the importance of adopting a life-cycle perspective to ensure equitable outcomes in decarbonization efforts.

Decarbonization practices can be examined from a just transition perspective, associating them with the different archetypes proposed by Karaosman et al. (2024). Figs. 3, 4, and 5 illustrate, for each theme presented in Section 3.1 (consumer attitude and behavior, optimization and quantification, challenges and obstacles), the decarbonization practices that are government/industry-led or involving civil society and profit or shared outcomes-oriented, reframing them in transitioning practices.

The practices, illustrated in Figs. 3, 4, and 5 with reference to the themes "Consumer attitude and behavior", "Optimization and quantification", and "challenges and obstacles" respectively, can be grouped by "Profit oriented" and "Shared outcome-oriented", leading to two groups of practices. Overlapping, namely, practices associated with more than one theme, are eliminated. Similar practices are rephrased, i. e., "Horizontal collaboration" linked to "Consumer attitude and behavior" (shared outcome oriented) and "Collaborative efforts to improve accessibility, technological exclusion, or country-specific regulations" linked to "Challenges and obstacles" (shared outcome oriented) are summarized as "Activate collaboration with the other actors along the supply chain". The practices "Improve collaboration between Logistics Service Providers (LSP) and retailers" and "Collaboration to improve vehicle-fill and reduce empty returns" linked to "Challenges and obstacles" (profit oriented) and "Collaboration among stakeholders to reduce excess inventory, shorten lead time, increase sales and customer service levels" linked to "Optimization and quantification" (profit oriented) are summarized again as "Activate collaboration with the other actors along the supply chain". Similar considerations were drawn up to summarize the other practices.

From the studies included in the review, a total of 101 decarbonization practices were extracted and coded for analysis. Among them, 60 % were led by governmental or industrial actors, 40 % involved civil society organizations. With respect to outcome orientation, 48 % of practices were categorized as profit-oriented, primarily aiming at financial or competitiveness outcomes, while 50 % were shared outcomes-oriented, emphasizing collective social and environmental benefits, and 2 % presented a combined approach. Cross-tabulation between actor type and purpose revealed a clear pattern: civil society-involved practices were substantially more likely to be shared outcomes-oriented (58 %) compared to government/industry-led ones (42 %). Conversely, profit-oriented practices were almost equally government/industry-led (55 %) and civil society-involved (45 %).

3.1. Themes

Our analysis allowed us to identify the recurring themes in the domain of last-mile decarbonization and the locations of the studies. The themes revealed were: 1) ***Consumer attitude and behavior***, grouping the papers with a focus on consumers' preferences and behaviors; 2) ***Optimization and quantification***, grouping the papers addressing optimization problems, efficiency improvement, and measurements; and 3)

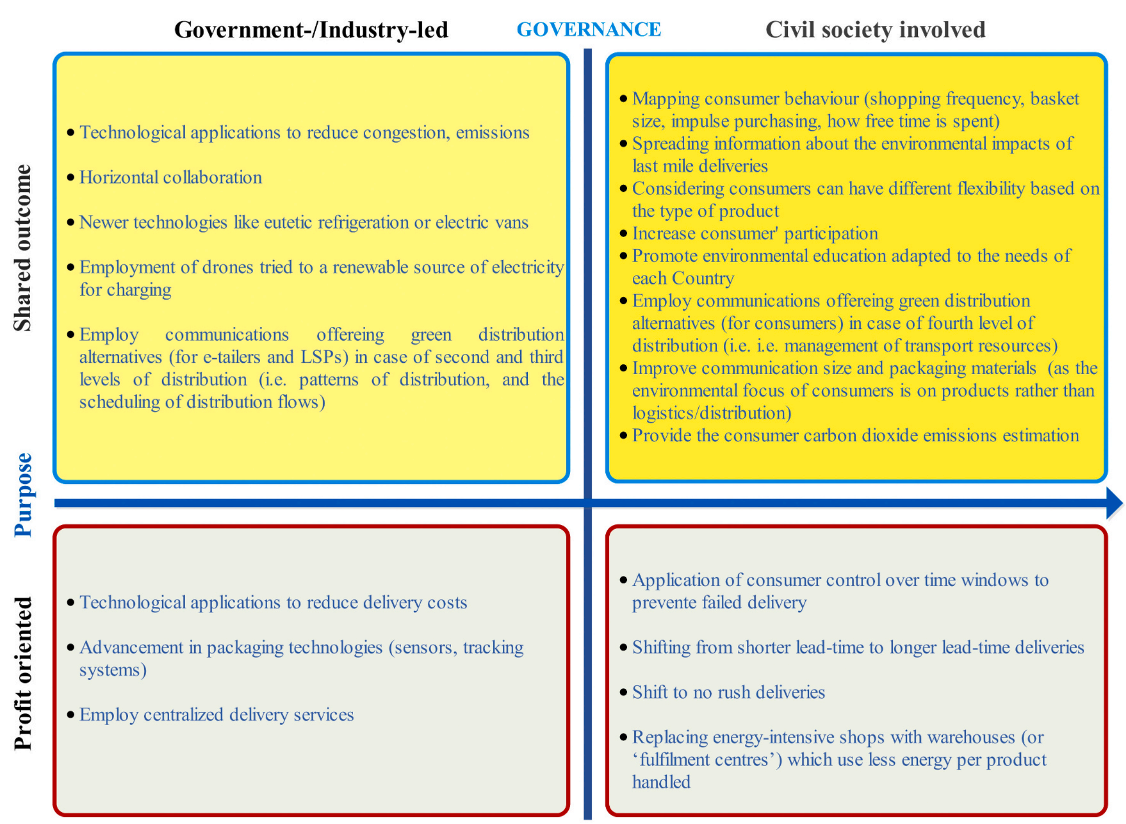

Fig. 3. Decarbonization practices associated with consumer attitudes and behavior reframed within the context of the just transition view.

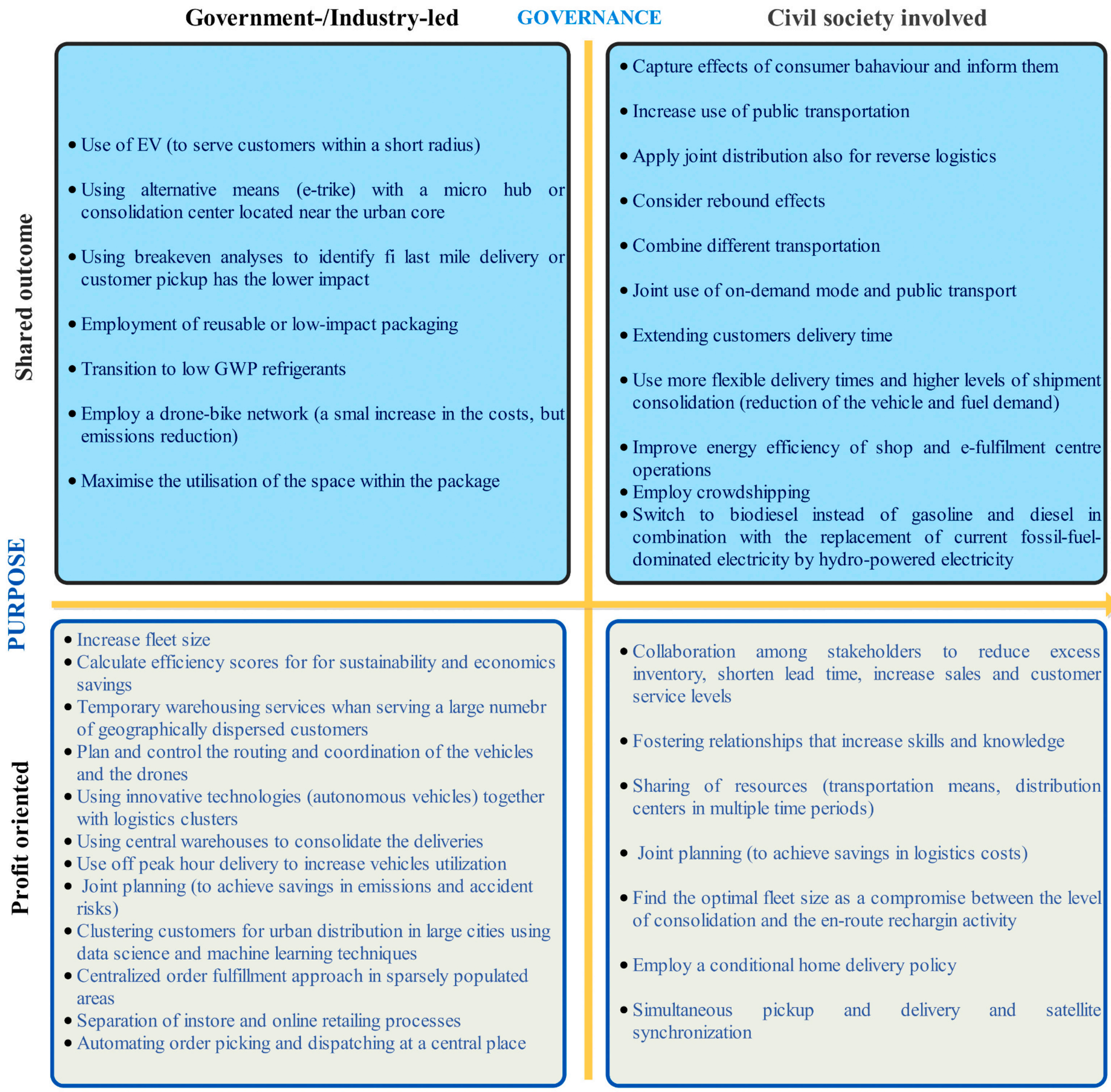

Fig. 4. Decarbonization practices associated with assessment reframed with the just transition view.

Challenges and obstacles, grouping papers addressing challenges, barriers, and change in last-mile management. The studies include a good variety of locations, covering different European Countries, and also China, the USA, Brazil, Mexico, and Australia. Seven studies addressed "Consumer attitude and behaviour", which centers on conceptual and policy framings of the *just transition*; four focused on "challenges and obstacles" associated with implementation, such as governance barriers or distributional conflicts; and the remaining 33 fell within the category of optimization and quantification approaches, dealing with modelling, metrics, or assessment tools for low-carbon transitions.

Table A5, reported in the Appendix, illustrates the list of studies, their themes, locations, research methods, and reports the main decarbonization practices suggested by the authors of the selected studies.

3.1.1. Consumer attitude and behavior

The locations of the studies, which spanned across the UK, Greece, the USA, Brazil, and Sweden, reflect distinct consumer behaviors and habits shaped by local contexts.

As the last-mile delivery segment represents the main contributor to carbon emissions in online retailing (Van Loon et al., 2014), understanding behavioral outcomes, consumers' attitudes, and behaviors in response to supply chain management strategies is critical. These outcomes directly influence key supply chain components such as delivery frequency, demand intensity, and structural adaptations, highlighting the power of consumer preferences in steering sustainable logistics solutions (Gee et al., 2020). In the Brazilian context, Nogueira et al. (2021) showed that several factors can influence their decisions, specifically focusing on whether they are willing to choose more sustainable options (such as slower delivery or higher costs) over faster delivery times and lower prices, and how they balance and prioritize sustainability, delivery time, and cost when making online orders. Providing consumers with information about the environmental impact of different delivery choices encourages them to make more sustainable decisions when ordering products online (Thomas et al., 2022), and consumers, along with e-tailers and logistics service providers, can communicate to encourage more sustainable distribution practices, as revealed by Sallnäs and Björklund (2020) in their study developed in Sweden. Horizontal collaboration in the last-mile delivery process can emphasize the benefits for both businesses in the supply chain and the environment. By collaborating, businesses can reduce the total distance traveled during deliveries, and optimization of routes and demand consolidation are essential for lowering travel distances, as discussed both for the UK and

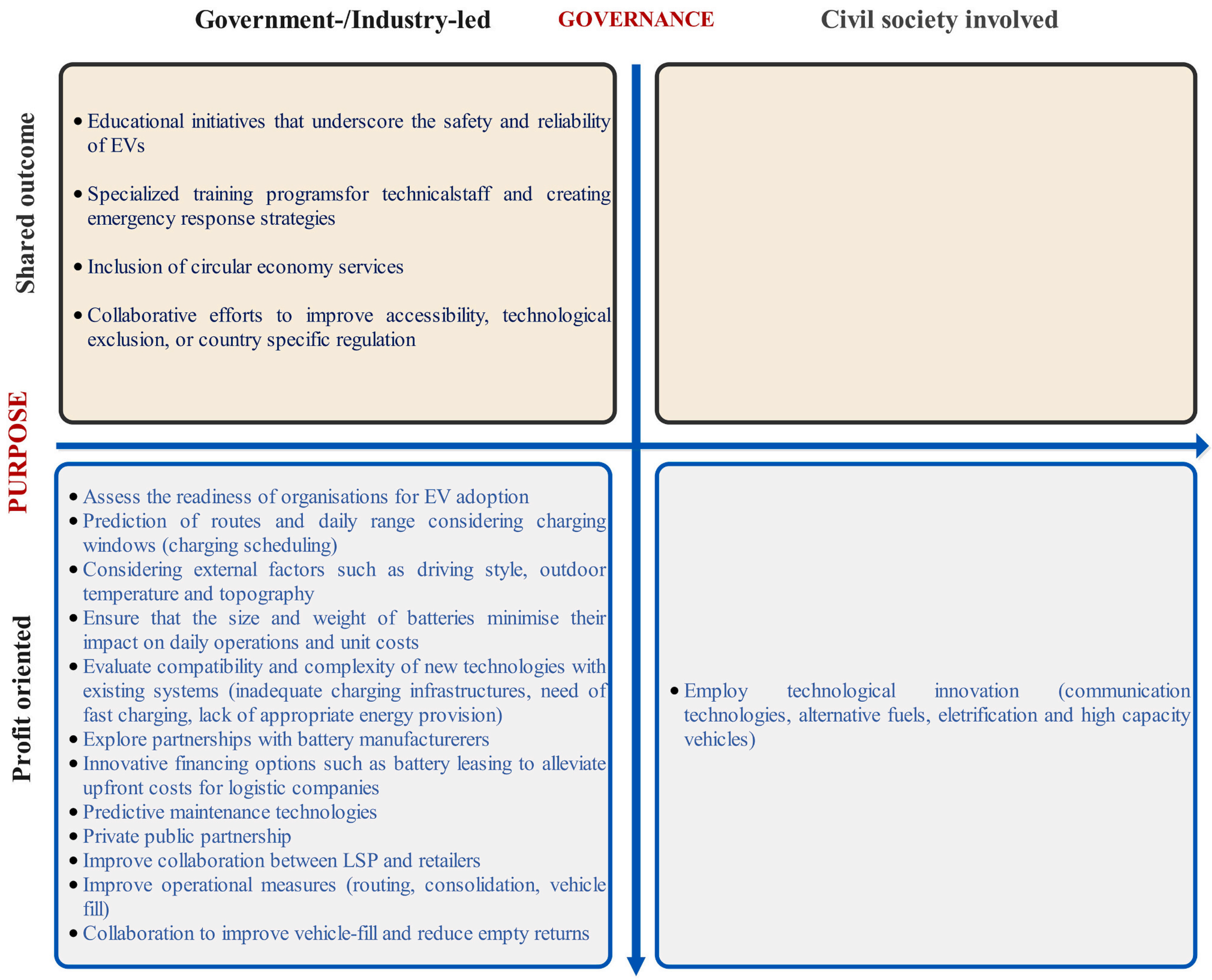

Fig. 5. Decarbonization practices associated with change reframed with the just transition view.

in Greece (Argyropoulou et al., 2023). Thus, investigating the CO_2 emissions associated with two key aspects of the retail experience, namely customer trips to physical stores and individual e-commerce deliveries, is uncovering trade-offs in last-mile delivery emissions, comparing the environmental impact of online shopping (with home delivery) versus driving to a retail location to pick up a product in the USA (Lerner et al., 2024). The practices are reported in Fig. 3.

3.1.2. *Optimization and quantification*

Collaboration is crucial for moving goods efficiently while managing urban challenges like congestion, emissions, and space constraints, entailing the need for collaboration and operational models (Adetiloye and Pervez, 2015). Optimization approaches are needed to establish effective collaborative strategies as revealed for a French case study (Aloui et al., 2021), implementing horizontal cooperation to improve financial and environmental impacts also in African contexts (Ouhader and El Kyal, 2023) and leveraging joint distribution also by combining shipments from different sources or businesses into a single delivery route, in a intensive context as the Chinese one (Hong et al., 2022; Nogueira et al., 2022). Smooth and efficient operations can be ensured by sharing information among supply chain members in the USA (Sarkar et al., 2024). Challenges related to resource management, time optimization, and cost reduction, particularly in light of growing environmental concerns, can be addressed through optimization models both in Europe and the USA (Hassan et al., 2024; Santiago-Montano et al., 2024). A novel joint delivery system that focuses on reducing operational costs and carbon emissions can be developed by encouraging horizontal cooperation and resource sharing among express delivery companies (Du et al., 2023), rethinking Australian logistics models to reduce emissions while meeting consumer demands (Wu et al., 2024) and planning a new on-demand freight delivery service with shared use of transportation options, as showed in a European context from Labarthe et al. (2024).

The use of automated warehouses, vehicles, and robots, along with shipment consolidation strategies and pick-up points, can introduce new possibilities for supply chains in Europe (Ramírez-Villamil et al., 2023), India (Prajapati et al., 2021) and South America (Muñoz-Villamizar et al., 2022) and face the need of innovation and transformation in the USA (Brown and Giuffrida, 2014) also in short-term in Europe (Andoh and Yu, 2023). The impact of drone delivery on the environment and cost has become a crucial area of research; however, integrating drone delivery into existing vehicle routing systems presents challenges that require effective vehicle routing optimization (Chiang et al., 2019). Investigating the diffusion of innovative vehicles, such as electric and hybrid commercial vans, while focusing on parcel delivery entails understanding several key factors, as reported in the study developed by Cagliano et al. (2017) performed in Italy. Some innovative solutions that have emerged are the use of smart parcel stations (Eliyan et al., 2021), vehicle routing problems with simultaneous pick-up and delivery and satellite synchronization (Zhou et al., 2024) while continuing to examine the impact of key technological and operational factors on the daily routing of battery electric trucks (Lin and Zhou, 2021) and the use of electric vehicles in delivery services also in Latvia (Scedrovs et al., 2024).

However, there are various trade-offs to consider that impact the overall efficiency of the delivery solutions in the USA (Gee et al., 2019), and simulation and optimization models can help address the trade-offs between sustainability and cost-effective performance in logistics and transportation in different places, including China (Gružauskas et al., 2018; Zhao and Lee, 2023).

Specific frameworks to optimize the entire supply chain are needed (de Oliveira et al., 2021), evaluating not just the direct impacts like greenhouse gas emissions and energy consumption but also considering indirect factors, such as packaging waste, supply chain emissions, and consumer behavior (Van Loon et al., 2015) also employing a life cycle-based approach (Heard et al., 2019; Hu et al., 2019). In addition, a flexible supply-demand matching mechanism for crowdsourcing logistics platforms can match consumers, businesses, and service providers, as shown in the study performed by Wang et al. (2024) and based in China. The practices are reported in Fig. 4.

3.1.3. Challenges and obstacles

Changes are mainly declining concerning challenges in adopting electric vehicles. Electric vehicles have the potential to reduce carbon emissions and improve sustainability in logistics significantly; however, several obstacles remain in terms of cost, infrastructure, and operational integration (Anosike et al., 2023), and addressing these barriers is needed to provide a comprehensive understanding of the challenges faced by supply chain stakeholders (Dadashzada et al., 2024). Efforts, challenges, and strategies involved in reducing carbon emissions in the road freight transportation sector include the use of electric vehicles, but also alternative fuels, efficiency improvements, modal shifts and innovations in logistics and routing (Meyer, 2020) and how managers implement sustainable practices in the final stage of the delivery process as discussed by Heikkinen (2024) in the European context. The practices are reported in Fig. 5.

3.2. Research methods

Our analysis allowed us to identify the recurring research methods in last-mile decarbonization, schematized in Fig. A1 (Appendix).

3.2.1. Consumer attitude and behavior

The study by Gee et al. (2020) employed a literature review method to explore the environmental implications of e-commerce. It highlights trade-offs within the grocery supply chain. It identifies gaps in existing research, and based on an extensive literature review, Van Loon et al. (2014) delved deeper into the broader carbon impacts associated with online retailing, including last-mile delivery. In their research, Thomas et al. (2022) conducted experiments in a simulated online shopping environment to understand how sustainability information affects consumer choices between two delivery options. Surveys were conducted involving respondents to understand how e-consumers prioritize various factors when making online purchases, specifically about delivery speed, cost, and sustainability (Nogueira et al., 2021) and to provide feedback on how environmental concerns influence their shopping preferences in combination with calculation of the net impact on tailpipe CO_2 emissions when comparing home delivery of e-commerce orders versus driving (Lerner et al., 2024). A combination of methods was also employed by Sallnäs and Björklund (2020), who used website scans and interviews to gather data on the environmental impact of e-commerce distribution. By combining quantitative data from website scans with qualitative insights from interviews, the researchers aimed to explore the communication gap between e-tailers, logistics service providers, and consumers regarding delivery options.

By focusing on the grocery markets in the United Kingdom and Greece, which differ in factors like online grocery penetration, distribution network structure, and delivery times, Argyropoulou et al. (2023) explored how resource pooling among businesses could bring about positive outcomes for various stakeholders.

3.2.2. Optimization and quantification approaches

Studies addressing optimization of collaboration employ different models, Adetiloye and Pervez (2015) developed a collaboration and operational matrix model considering the transactions among businesses and customers, while Aloui et al. (2021) used a two-echelon inventory, location, and routing problem to elaborate, with a specific focus on reducing both logistics costs and CO_2 emissions. A two-echelon location-routing problem to integrate different decision levels and investigate the trade-offs between the two conflicting objectives was also used by Ouhader and El Kyal (2023). By using a real-world case, specifically in Songjiang University Town of Shanghai, China, the study of Hong et al. (2022) explores the potential benefits of joint distribution compared to traditional separate delivery systems and a discrete event simulation is employed to create scenarios that highlight the benefits and challenges of various delivery time options based on consumers' decisions regarding the flexibility of these time slots (Nogueira et al., 2022). Sarkar et al. (2024) solve a supply chain management model under a dual-channel retailing strategy with data-sharing policies using classical optimization techniques and integer programming. Meanwhile, Santiago-Montano et al. (2024) address the two-echelon multi-trip capacitated vehicle routing problem with home delivery and optional self-pickup services. Also, Ramírez-Villamil et al. (2023) employed a two-echelon parcel distribution network model to minimize environmental impacts, reduce travel times, and optimize resource use. Mixed-integer linear programming is often applied, addressing CO_2 emissions and cost reductions (Muñoz-Villamizar et al., 2022; Chiang et al., 2019), for vehicle routing problems (Zhou et al., 2024).

A multi-depot two-echelon joint delivery location routing problem was used to optimize both vehicle routing and location selection for a system in which multiple depots collaborate to deliver goods (Du et al., 2023; Andoh and Yu, 2023), and a multi-method approach was used for analyzing the cost and carbon emissions between the existing and proposed logistics approaches is a comprehensive strategy that integrates multiple techniques to understand different delivery models (Wu et al., 2024: Eliyan et al., 2021). An on-demand multimodal transshipment problem was addressed using a model-based decision support approach (Labarthe et al., 2024), and an optimization model including carbon emission taxes, inventory holding, and vehicle emissions was applied by Prajapati et al. (2021) and Azad et al. (2023). Lin and Zhou (2021) elaborate on cost metrics, and Gee et al. (2019) employed a Monte Carlo simulation to model and analyze the uncertainties and variations in operating conditions. Gružauskas et al. (2018) proposed an approach to managing the logistic cluster that aims to mitigate the trade-offs between sustainability and cost-effective performance. Wang et al. (2024) developed a dual-system design consisting of two parallel and independent matching systems aimed at enhancing the flexibility and adaptability of supply–demand matching mechanisms in crowdsourcing logistics platforms.

A system dynamics model based on Bass diffusion theory was used to simulate the adoption of low-emission vehicles (Cagliano et al., 2017). A comprehensive comparison of carbon emissions between conventional shopping involving customer pick-up with trip chaining and e-commerce-based online retailing involves analyzing various factors that contribute to emissions developed (Brown and Giuffrida, 2014), including cost metrics (Lin and Zhou, 2021). Zhao and Lee (2023) used simulation parameters.

A life cycle-based approach was used to analyze 72 routes that a 36-item grocery basket could take from a centralized warehouse to the customer's residence, using both traditional and e-commerce pathways (Kemp et al., 2022), to explore the costs and benefits of fleet electrification (Scedrovs et al., 2024) and to adapt city logistics for urban farming (Hu et al., 2019; de Oliveira et al., 2021). A life cycle-based approach was then used to evaluate the environmental impact of various methods for goods, highlighting the need to include a variety of consumer shopping behavior variables (Van Loon et al., 2015; Heard et al., 2019), such as off-peak hour deliveries (Hassan et al., 2024) and different modes for home delivery (Álvarez-Rodríguez et al., 2020).

3.2.3. Challenges and obstacles

Anosike et al. (2023) developed a systematic literature review, which served as a crucial step in identifying the key challenges of adopting electric vehicles for last-mile deliveries and provided a structured overview of the issues involved. The findings from the literature review set the stage for the next phase of research, where in-depth interviews with logistics companies. Meyer (2020) also employed the literature review method using bibliographic coupling and network analysis techniques. Heikkinen (2024) adopted a multiple case study to explore how retailers and logistics service providers understand and address the sustainability challenges in last-mile deliveries, allowing for a detailed and contextual examination of the decision-making processes within organizations across different case settings. Dadashzada et al. (2024) identified 21 critical barriers to the deployment of electric vehicles (EVs) in last-mile deliveries (LMDs), and these barriers were validated through a quantitative survey involving 157 supply chain experts. The survey data were analyzed using Exploratory Factor Analysis and Analytical Hierarchy Process (AHP).

These studies demonstrate the breadth of methodological approaches employed to investigate last-mile decarbonization—from qualitative, literature review and quantitative to advanced optimization and simulation models. This diversity highlights the interdisciplinary nature of the field and the need for integrated methods that capture consumer behavior, assessment, and organizational change.

4. Discussion

This section discusses the unintended socio-ecological side effects that may arise from last-mile decarbonization and the different pathways. While decarbonization is often associated with environmental benefits, this study reveals that it can also produce a range of complex and sometimes adverse consequences that are usually overlooked. To reveal unintended side effects, firstly, the decarbonization practices are framed based on their purpose as suggested by the taxonomy proposed by Karaosman et al. (2024) in shared outcomes or profit-oriented (Section 4.1). Secondly, the practices are interpreted through the life cycle thinking, as a systemic perspective to identify hidden burdens along the supply chain (Section 4.2), giving an answer to RQ2. All the cases from the reviewed literature are mapped in Table A5 (Appendix), which presents the thematic groups, illustrates for each case the main decarbonization practices suggested by the authors, classifies them based on the purpose and the type of governance, and the labelling based on the type of decarbonization practices. Possible unintended side effects based on the life cycle thinking with a supply chain view are revealed.

4.1. Shared outcomes and profit-oriented decarbonization practices

The decarbonization practices presented in Section 3 are now grouped as practices oriented to improve sharing of information and resources and labelled “Sharing” (i.e. spreading information across different actors, training, collaboration with other actors along the supply chain, communication with other actors along the supply chain, increase of consumer participation), practices to model emissions and costs labelled as “Modelling” (i.e. use of breakeven analyses, estimation of emissions, considering rebound effects, mapping consumer behavior), practices regarding materials and equipment needed, labelled “Sourcing” (i.e. use of new technologies, use of alternative transport means, studying advancement in packaging, transition to low global warming potential refrigerants), and practices regarding “Operations” (i.e. employment of joint distribution, improvement of operations in terms of energy efficiency, routing, consolidation, employment of crowd shipping, development of circular services, employment of public transportation), as illustrated in Fig. 6 and Fig. 7.

Among the decarbonization practices identified, a subset of 20 was classified under the category of sourcing practices, referring to initiatives focused on sustainable procurement, supply chain decarbonization, or low-carbon material sourcing. Of these, 19 were industry-led and only one involved civil society participation, indicating that sourcing-related initiatives are predominantly driven by private sector or industrial actors rather than community or multi-stakeholder collaborations. In terms of outcome orientation, five of these sourcing practices were categorized as profit-oriented, primarily aimed at improving competitiveness, reducing costs, or meeting market-driven sustainability standards. The remaining 15 were shared outcomes-oriented, emphasizing cooperative approaches along the value chain and broader environmental or social co-benefits, such as reduced resource dependency or improved transparency in supply systems. This distribution suggests that, even within industry-dominated domains, a considerable share of sourcing initiatives is increasingly framed around collective and sustainability-oriented outcomes rather than purely economic objectives.

Beyond sourcing, 27 practices were classified under the category of sharing, which includes initiatives centered on knowledge exchange, collaborative platforms, or shared resource use. Among these, 17 involved civil society participation and 10 were government–industry led. The majority (21 out of 27) were oriented toward shared outcomes, regardless of whether they were civil-society-driven or institutional collaborations, underscoring the strong cooperative dimension of sharing-based decarbonization efforts.

A further 30 practices fell within the operations category, equally divided between civil society-involved and government–industry-led initiatives. These practices were predominantly profit-oriented (22 out of 30), reflecting a focus on efficiency improvements, technological optimization, and process innovations that yield measurable economic benefits alongside emissions reductions.

Additionally, 13 practices were classified as modelling initiatives, encompassing approaches based on scenario development, forecasting, or systemic planning tools. Of these, eight were government–industry-led and five involved civil society actors. In terms of purpose, approximately half of these modelling practices were shared outcome-oriented, while the remaining half were primarily profit-oriented, indicating a balanced orientation between collaborative and competitive objectives within this category.

Finally, nine practices could be viewed as hybrid forms, combining elements of operations with sharing, sourcing, or modelling approaches. Seven of these were government–industry led, and an equal number (seven) were profit-oriented, suggesting a pragmatic blending of domains aimed at aligning cross-sectoral collaboration with economic feasibility. Two additional practices combined sourcing and modelling dimensions, highlighting the increasingly integrative nature of decarbonization strategies across practice types.

4.1.1. Patterns across geographical scopes

In the studies conducted in Europe, emphasis is placed on shared outcomes, reflecting both environmental and social concerns. However, profit-oriented initiatives are also present, particularly in countries like France, Italy, and the UK. In terms of governance, there is a balance between government-/industry-led efforts and civil society involvement, including collaboration between public authorities, private stakeholders, and the community. Last-mile decarbonization practices studied in Europe, based on the studies included in our sample, mirror a societal model in which last-mile decarbonization is not only the responsibility of governmental institutions or industrial actors, but also an outcome of a collective, multi-level engagement. In this context,

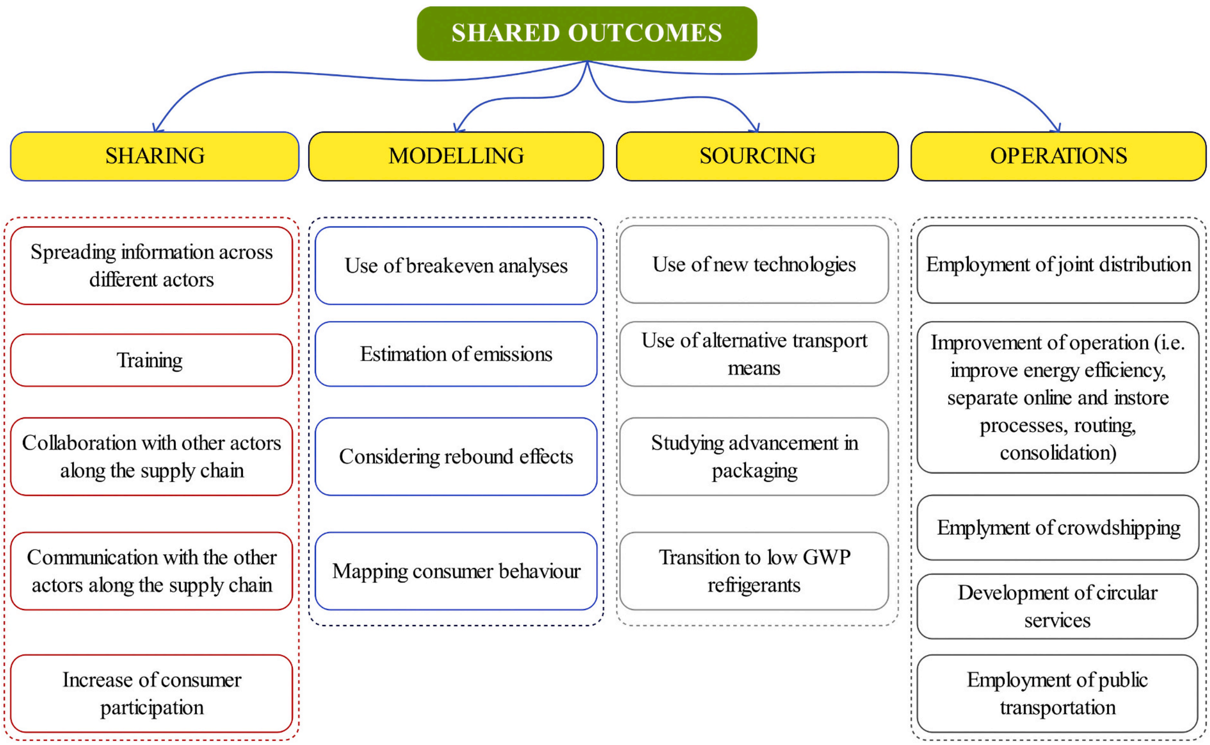

Fig. 6. Shared outcome-oriented transitioning practices grouped into 4 sub-groups.

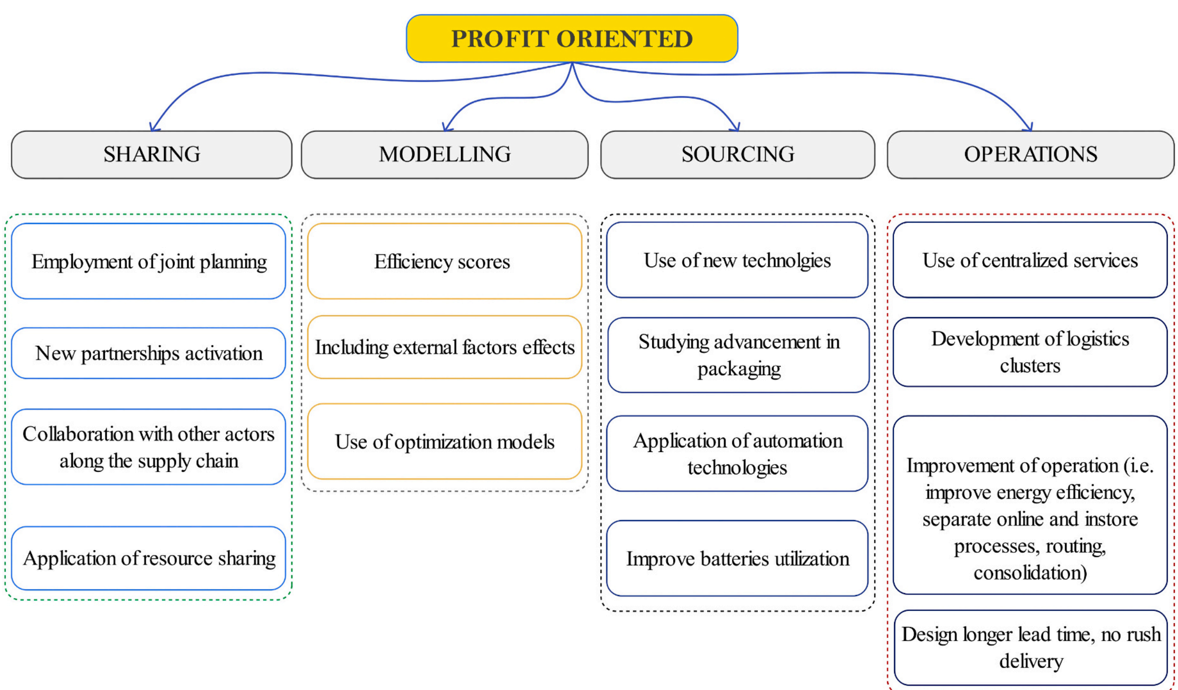

Fig. 7. Profit-oriented transitioning practices grouped into 4 sub-groups.

consumers, companies, and public authorities are engaged to actively collaborate to integrate technological innovation and operations optimization with environmental and social values. Regarding the decarbonization approaches analyzed in the United States and Australia, a mixed orientation toward both shared outcomes and profit emerges. Governance is largely government- and industry-led, although civil society involvement also plays a significant role, reflecting a societal model shaped by market-driven logics, where innovation and decarbonization efforts are often aligned with economic profits and technological leadership. In the studies conducted in Brazil and Mexico, the focus is predominantly on shared outcomes, with the main practices including consumer awareness, electric vehicles, and delivery slots, particularly relevant in regions facing rapid urban transformation.

Studies conducted in countries such as China and India show an inclination toward shared outcomes, balancing environmental priorities with operational efficiency. Governance is mixed. Many initiatives are led by governments and industry, but civil society also contributes, especially in crowd-based logistics. Main practices analyzed are crowd logistics, distribution optimization, mirroring a societal model in which decarbonization is aligned with the goals of economic growth and operational efficiency. In the only study conducted in Africa, the focus is on shared outcomes, while governance is government- and industry-led, reflecting top-down efforts to implement structural improvements to foster collaboration between competing shippers.

4.1.2. Patterns across research methods

The methods of research emerging from the selected studies were qualitative, based on text analysis, and quantitative, based on statistical analysis, and mathematical modelling methods (including optimization models, multi-criteria decision-making models, life cycle-based models), as illustrated in Fig. A1 (reported in the Appendix). The studies employing qualitative approaches reveal three main practices: developing circular services, collaborating with other actors along the supply chain, and enhancing communication. The studies using quantitative approaches highlight practices such as spreading information across different actors, increasing consumer participation, estimating emissions, mapping consumer behavior, designing longer lead times, promoting no-rush deliveries, and providing communication and training. Studies employing mathematical modelling suggest an even greater number of practices, as they also represent the largest share of the studies selected for this research. Through multimethod studies, the use of new technologies, of alternative transport means, improving batteries' utilization, training, efficiency score calculation, and new partnerships activation emerge as practices.

4.2. Revealing unintended side effects from decarbonization

The decarbonization practices along the supply chain can be examined from a life cycle perspective, associating them with the different life cycle stages (Toniolo et al., 2024).

The 4 sub-groups of practices, as reported in Figs. 6 and 7, both profit and shared outcomes oriented, are interpreted using the life cycle thinking. For each sub-group of practices, the life cycle thinking perspective allows identifying the impacts on society and the environment to be considered in order to achieve decarbonization in environmentally and socially just ways (Pagell and Wu, 2009).

Just transition embraces not only the environment, but also communities, workers, and other stakeholders, to create collaborative social dialogues. Profit-oriented practices could neglect the impacts of producing raw materials or the disposal of the generated waste flows. On the other hand, focusing on decarbonization often entails concentrating on emissions reduction, especially if cost savings are achieved. Multilevel government could be enhanced by community consultation and inclusion, contributing to economic growth and better worker conditions. Thus, the life cycle perspective, declined in its social and environmental dimensions, can help achieve a just transition, avoiding focusing on just one improved decarbonization aspect and shifting the problems from carbon emissions to other environmental categories. Fig. 8 illustrates how the sub-groups of decarbonization practices regarding **"Sharing"**, "Modelling", "Sourcing", and "Operations" can generate unintended side effects in other parts of the supply chain and identifies the impacts nested and indirectly connected with the provision of the last mile. To address unintended side effects generated by practices related with "Sharing," it will be important to consider the impacts on communities in the territories where raw materials are extracted, stored, processed, treated as waste, and where they transit, along with the impacts on the workers. To address side effects generated by practices related to "Modelling", socio-ecological indicators regarding the use and production of raw materials, distribution activities, the last mile delivery itself, and the generated waste have to be built. With reference to "Sourcing" and "Operations" practices, the side effects could be associated with new materials and equipment, their transportation, their production, the delivery itself, and the generated waste, which needs to be considered. The possible unintended side effects arising from decarbonization practices, which can be revealed using a just transition view from a life cycle perspective, are reported in Fig. 8. This step enabled the assessment of potential side effects without merely shifting environmental or social impacts from one stage or actor to another.

In light of the findings, a set of resolution strategies (Fig. 9) can be developed to address the environmental and social burdens identified within the last-mile logistics system. These strategies aim to reduce emissions and resource consumption and foster more equitable practices

LIFE CYCLE STAGES	POSSIBLE UNINTENDED SIDE EFFECTS DUE TO SHARING PRACTICES	POSSIBLE UNINTENDED SIDE EFFECTS DUE TO MODELLING PRACTICES	POSSIBLE UNINTENDED SIDE EFFECTS DUE TO SOURCING PRACTICES	POSSIBLE UNINTENDED SIDE EFFECTS DUE TO OPERATIONS PRACTICES
RAW MATERIALS EXTRACTION	• Effects on community and workers in the areas of raw materials extraction	• Indicators neglecting raw materials extractions • Modelling the use of raw materials without a social perspctive	• Environmental impacts due to new materials and equiment needed (i.e. biodiversity loss, utilization of scarse resources) and effects on community and workers	• Environmental impacts due to resources/other materials to provide the service (energy production, water consumption for operations) and effects on community and workers
DISTRIBUTION OF RAW MATERIALS/INTERMEDIETE GOODS/COMPONENTS	• Effects on community and workeers in the areas of materials transition and storage	• Indicators neglecting raw materials transportation • Modelling trasportation without a social perspctive	• Environmental impacts due to trasportation of new materials and equipment; effects on community and workers in the areas of materials transition and storage	• Environmental impacts due to transportation of resources/other materials to provide the service and effects on community and workers
PRODUCTION OF MATERIALS/INTERMEDIETE GOODS/COMPONENTS	• Effects on community and workers in the areas of production of the new raw materials needed	• Indicators neglecting raw materials production • Modelling production of raw materials without a social perspctive	• Environmental impacts due to trasportation of new materials and equipment and effects on community and workers	• Environmental impacts due to the production of resources/ other materials to provide the servicand effects on community and workers
DELIVERY	• Effects on community and workers in the areas of last mile delivery	• Modelling delivery without a social perspctive	• Environmental impacts due to materials and equipment for the delivery and effects on community and workers	• Environmental impacts due to operations needed to provide the last mile delivery and effects on community and workers
END OF LIFE OF GENERATED WASTE	• Effects on community and workers in the areas of the treatment of waste generated	• Indicators neglecting generated waste • Modelling waste generated without a social perspctive	• Environmental impacts due to waste generated (materials maintainance/demages) and effects on community and workers	• Environmental impacts due to the the treatment of waste generated during operations and effects on community and workers

Fig. 8. Possible unintended side effects arising from last-mile decarbonization practices using a just transition view from a life cycle perspective.

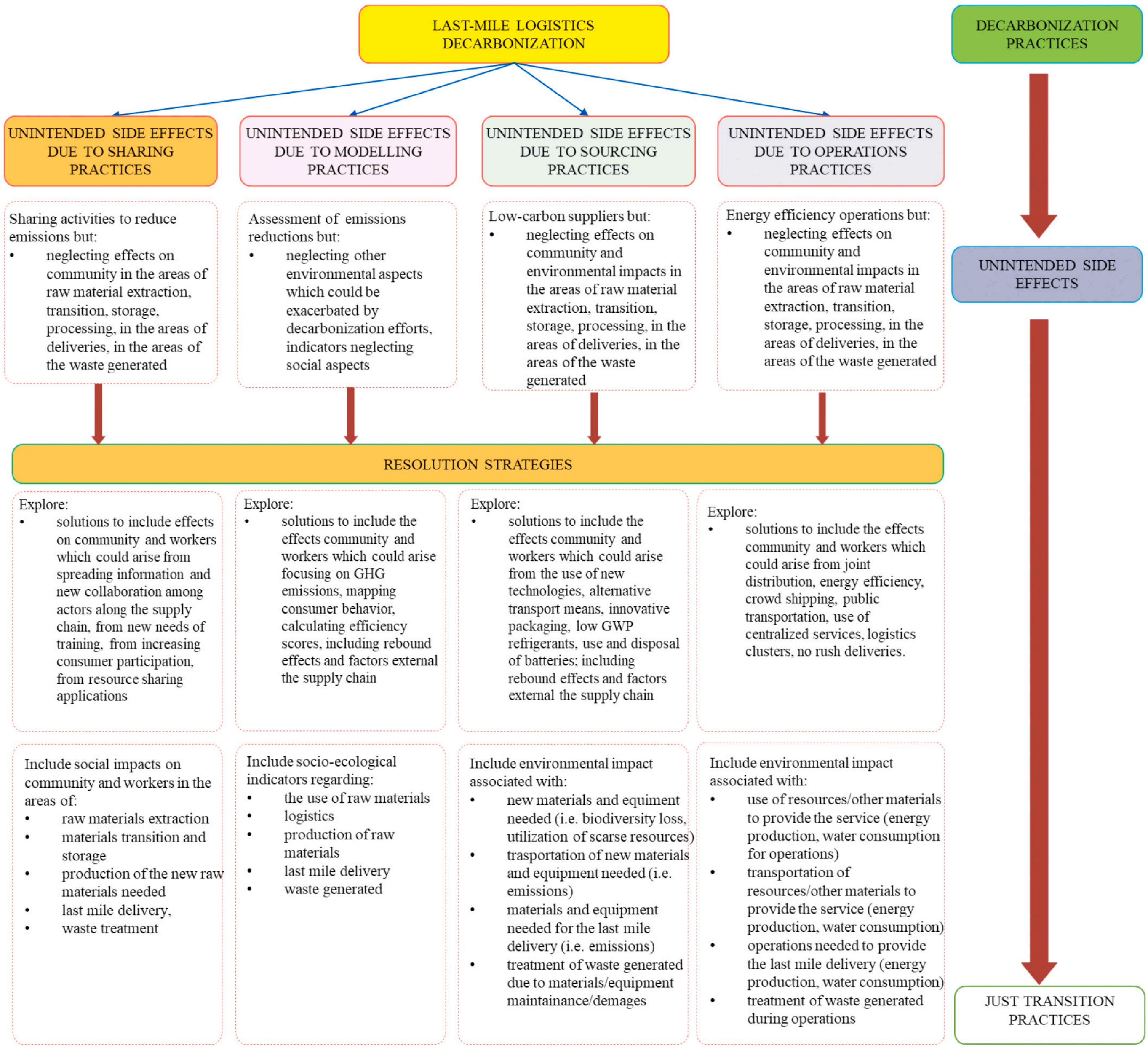

Fig. 9. Unintended socio-ecological side effects arising from last-mile decarbonization and possible resolution strategies.

along the supply chain, contributing to a broader vision of decarbonization efforts. The development of these strategies can be approached in two complementary ways: by exploring innovative directions that challenge conventional decarbonization activities and deliberately including often-overlooked environmental and social dimensions critical to achieving truly just outcomes. With reference to the unintended side effects due to sharing practices, the development of resolution strategies may benefit from exploring and expanding the scope of analysis to include communities and workers involved in raw material extraction, transportation, storage, and processing, as well as those affected by last-mile deliveries and waste management processes, and also integrating the effects on communities and workers directly into the design and evaluation of last mile logistics systems. Such inclusion is essential to ensure that resolution strategies address environmental concerns and social equity across the entire supply chain. Similar resolution strategies can be drawn for modelling practices, sourcing, and operations practices.

In the transition toward decarbonization, new perspectives are needed, ensuring that the shift to low-carbon systems does not exacerbate inequalities, moving beyond emissions-focused solutions and incorporating a broader vision (van der Veen et al., 2025; Le et al., 2024). Social effects need to be central in the design and assessment of decarbonization practices, through frameworks able to identify and mitigate them across different industrial and geographical contexts (Fortier et al., 2019). Operations management and supply chain decisions toward decarbonization need to be evaluated not only from an environmental perspective but also with reference to their long-term societal impacts (Karaosman and Marshall, 2023). Decarbonization efforts need to be embedded in social structures, as it is not just a matter of just moving away from fossil fuels, but also restructuring systems and safeguarding affected communities (Abram et al., 2022). Under this light, the just transition framework plays a crucial role in aligning environmental goals with social principles of equity, ensuring that the decarbonization is not assessed solely in terms of technological innovation or emissions reduction (Creti and Ftiti, 2024; Ferreira de Silva et al., 2024). Just transition addresses the long-term social effects to mitigate spatial and temporal disparities and helps transform structural challenges involving communities, shifting the focus from managing to planning for regeneration (Mark et al., 2024).

4.3. Refining the interpretation

The sensitivity analysis allowed for assessing the robustness of the qualitative synthesis to methodological variation. First, the synthesis was repeated, including only studies rated as having *high appropriateness* according to the quality appraisal criteria. Second, only studies with *complete boundaries* were retained, in order to test the potential influence of study completeness on the thematic grouping. Third, only studies classified as "consumer attitude and behaviour", as "optimization and quantification approaches", and finally as "challenges and obstacles" were included, separately, as summarized in Table A6 (Appendix). Table A7 (Appendix) reports the occurrence and stability of different types of decarbonization practices across the analytical subsets considered. The four main categories of practices (*sourcing*, *sharing*, *operations*, and *modelling)* were examined for their presence within the full synthesis, within the "High Appropriateness" and "Complete Boundaries" subsets, and within each theme. Results indicate that *sourcing*, *sharing*, and *operations practices* are consistently present across all subsets, demonstrating a high degree of stability and robustness in the analysis. Their recurrence suggests that these categories represent core and widely acknowledged approaches to decarbonization across the reviewed literature. *Modelling practices* appear less consistently: while they emerge in the full synthesis and in the subset analyses, their presence within the "Complete Boundaries" group is only partial, being identified in a single paper and in combination with *sourcing* practices. This partial occurrence indicates that *modelling practices* are comparatively sensitive to variations in the analytical scope and completeness criteria, suggesting a lower degree of stability and a more context-dependent role within the field.

5. Conclusion

This paper has explored how last-mile logistics can contribute to decarbonization efforts and align with the broader goals of a just transition approach. The study uncovers a range of practices from diverse research fields that support last-mile decarbonization by addressing two research questions. It highlights that decarbonization is not a one-dimensional challenge; instead, it involves trade-offs, interdependencies, and context-specific solutions. Our analysis reveals a diverse range of last-mile decarbonization practices shaped by different societal models and regional locations. Some practices reflect a commitment to both environmental and social outcomes, while others are more aligned with profits logics or operational efficiency. These diverse patterns suggest that last-mile decarbonization is addressed not uniformly across different contexts, reflecting local conditions and priorities. However, while several studies included in our analysis are conducted in a specific geographical context, some of them do not explicitly define their geographical scope, limiting the possibility to fully interpret how the types of societies, the cultural norms, or the structure of governance can affect last-mile decarbonization practices.

Our systematic literature review enabled the identification of recurring themes and subgroups of decarbonization practices. These practices were then reinterpreted through the lens of just transition and life cycle thinking, revealing the potential to evolve from isolated decarbonization measures into more holistic and equitable practices. This led to the proposal of a structured taxonomy to identify just transitioning practices for last-mile logistics.

Importantly, the analysis also highlights that some decarbonization practices can generate unintended socio-ecological side effects, particularly when social dimensions are overlooked or when environmental goals are pursued in isolation. By exposing these side effects, the study contributes to bridging supply chain management, operations, and logistics management research with a just transition approach, emphasizing that successful transformations require attention to environmental outcomes, social equity, and systemic integration.

5.1. Practical implications

For practitioners, our results provide actionable insights into how decarbonization can be operationalized beyond technical fixes. Managers should recognize that decarbonization practices can be embedded within broader transition strategies, taking into account their social and economic impacts. By adopting life cycle thinking, firms can avoid problem shifting and ensure that improvements in one area (e.g., emissions reduction) do not create burdens in another (e.g., labor conditions or local communities). Moreover, classifying practices into civil-society-involved and industry-led efforts helps managers identify where stakeholder collaboration is most needed. Embracing the just transition framework also encourages companies to design last-mile delivery solutions that promote a shift toward more socially acceptable and understandable models from the consumer's perspective. This approach enables a better balance between environmental performance, decarbonizing practices, and consumer expectations, particularly regarding delivery speed, cost, and service reliability.

5.2. Policy implications

The findings have several implications for policymakers seeking to enhance urban logistics from a social-ecological perspective. First, policies should support multi-stakeholder collaboration, recognizing that last-mile delivery is not merely a commercial function but a vital public service and a cost for a community. Urban logistics systems must be designed as part of a collaborative urban ecosystem, where public and private actors work together to reduce environmental impacts while ensuring efficient and equitable service delivery. Second, policy frameworks should incentivize collaborative practices that involve multiple stakeholders, including industry, local authorities, and civil society, to achieve environmental, social, and economic objectives in an integrated manner. This approach helps avoid siloed policies that narrowly target emission reductions without considering broader systemic impacts. Integrating a just transition perspective can enhance the operational feasibility of decarbonization by aligning environmental goals with social equity, including strong social dialogue with local communities and underrepresented groups (Karaosman et al., 2024).

The application of life cycle thinking can further support policy design by offering a holistic view of potential trade-offs, preventing problem shifting, and promoting system-wide benefits.

5.3. Limitations and further research

While this study provides a thorough overview through a systematic literature review, the method naturally limits insight into real-time dynamics and the subtleties of operational settings. One notable limitation is the lack of empirical validation for identified patterns and practices. To advance understanding of how transition principles play out in practice in the context of last-mile delivery, future studies should adopt empirical approaches that reveal experiences and the evolving nature of transitions within diverse contexts, including municipality contexts, examining practices that involve civil society and are shared outcomes-oriented.

Another limitation of this study lies in its reliance on a supply chain perspective, as guided by Lim et al. (2018). While this lens provided conceptual consistency with our focus on last-mile decarbonization, it also created boundaries that may have excluded relevant urban or last-mile studies not explicitly framed within supply chain discourse. In our methodology, "supply chain" served as a boundary condition during database searches, anchoring the analysis within operations, logistics, and distribution literature. This naturally filtered out adjacent areas such as urban mobility, transportation engineering, and ICT-driven traffic systems. Future research could expand these boundaries by integrating both supply chain and transport system perspectives, or by using broader search terms to capture a wider range of studies on urban optimization, transport economics and decarbonization.

Additionally, the article search process presents limitations related to both keyword selection and database coverage, relying solely on the ISI Web of Science database. The focused keyword strategy, while maintaining alignment with the study's objectives, may have omitted relevant works addressing last-mile decarbonization without explicitly using the selected terms in their title, abstract, or keywords, for instance, research on specific materials supply chains and pooling in urban logistics. Future research could enhance comprehensiveness by integrating multiple databases and combining supply chain and transport system perspectives to capture a broader range of studies on urban logistics and decarbonization. Additionally, although the notion of a just transition seeks to align environmental aims with social equity, its practical links to the supply chain are still not well defined. This review starts by identifying decarbonization practices in last-mile logistics that attempt to balance efficiency with social and ecological concerns, including the impacts on communities in the territories where raw materials are extracted, stored, processed, treated as waste, and where they transit. Yet, more research is needed to turn these insights into actionable strategies that genuinely reflect the priorities of communities, individuals, and the environment, also for different geographical scopes.

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CRediT authorship contribution statement

Sara Toniolo: Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing - revised draft. **Ivan Russo:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing - revised draft. **Jingzheng Ren:** Writing – original draft, Visualization, Validation, Investigation, Writing - revised draft. **Md. Abdul Moktadir:** Writing – original draft, Visualization, Validation, Investigation, Data curation, Writing - revised draft.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sara Toniolo reports travel were provided by Vicenza Univr Hub (VUH). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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