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RESEARCH ARTICLE

Sustainable Last-Mile Transportation in Smart Cities: A Systematic Literature Review, Technology Taxonomy, and Research Agenda

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ABSTRACT

The Smart City (SC) is increasingly regarded as a complex adaptive system in which citizens, resources, and services interact dynamically, and sustainable Last-Mile (LM) transportation has emerged as one of its most pressing operational challenges. This article presents a full systematic literature review (SLR) of the field, conducted according to the PRISMA 2020 protocol, and organized as a comparative study of the technological and organizational solutions proposed to reduce LM externalities in smart cities. The review is based on a corpus of 60 references (58 included studies and two methodological references) spanning 2006–2026, with a dedicated focus on four families of emerging solutions: electric vehicles (EVs), autonomous delivery robots (ADRs), unmanned aerial vehicles (drones), and shared/collaborative urban infrastructure (cargo bikes, micro-hubs, and consolidation centers). Beyond a narrative review of smart-city concepts and last-mile externalities, this study introduces an explicit review methodology with a PRISMA flow diagram, a structured technology taxonomy illustrated with comparative charts, an enlarged comparative table of 16 empirical and review studies, and a dedicated discussion section that confronts the identified trends with the research gaps reported in the literature. The findings confirm that no single technology can resolve the sustainability–efficiency trade-off of urban freight in isolation; instead, hybrid fleets, shared infrastructure, and collaborative governance mechanisms appear as the most promising directions. The paper concludes with a structured set of future research directions addressing methodological, technological, and policy-oriented gaps for the sustainable transformation of last-mile logistics in smart cities.

KEYWORDS: Last-Mile Transportation · Smart City · Sustainable Logistics · Systematic Literature Review · Emerging Delivery Technologies · Research Agenda

1. Introduction

The share of the world population residing in urban areas is growing continuously [1, 2]. Combined with the exponential growth of e-commerce and globalized markets, this urbanization trend has turned cities into the final and most complex link of virtually every supply chain [3, 4, 5]: goods purchased anywhere in the world

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are, in the vast majority of cases, ultimately delivered within a dense urban environment. The resulting Last-Mile (LM) delivery problem is being addressed through the development of Intelligent Transport Systems (ITS), Information and Communication Technologies (ICT), and innovative delivery vehicles [6, 7, 8, 9]. The growing urban population requires increasing volumes of resources, freight, and services, generating a range of negative externalities for society [10, 11, 12, 13, 14], among which air pollution, noise, congestion, accidents, climate change, and infrastructure degradation are the most frequently studied in the scientific literature. This article presents an extended and methodologically formalized systematic review of this problem[1], organized as a comparative study of the technological and organizational solutions available to reduce last-mile externalities in smart cities.

Climate change, driven largely by greenhouse gas (GHG) emissions, is one of the most significant issues in contemporary transportation planning. Intensive automobile use including freight vehicles generates congestion, which is costly in both time and money, while also accelerating the deterioration of urban infrastructure. Nonetheless, transportation activity remains a pillar of social and economic life, encompassing both the movement of people and the movement of goods, across air, rail, road, and maritime modes. Within this context, the Smart City (SC) paradigm has become central to how affluent, industrialized nations envision sustainable urban development. Its main pillars solid waste management, sanitation, affordable and intelligent housing, sustainable energy, efficient public transit, and clean urban mobility [15, 16, 17] are increasingly supported by digitalization, the Internet of Things (IoT), artificial intelligence (AI), and machine learning (ML) [18, 19, 20].

Road remains the dominant mode for LM delivery, although alternative modalities (e.g., river transport where waterways exist) are used depending on local geography. In dense urban areas, road freight transport is the primary source of delivery-related externalities, largely because shippers rely on numerous, often uncoordinated carriers and logistics service providers. This fragmentation results in redundant routes, low vehicle fill rates, high externalities, and elevated system costs challenges that are central to the implementation of sustainable LM services in smart cities [16].

This study synthesizes the literature on LM transport in smart cities through an explicit, replicable review methodology based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [21], including a documented search strategy, eligibility criteria, and a PRISMA flow diagram. Building on an enlarged literature base of 60 references (58 included studies and two methodological references), of which eleven sources (ten peer-reviewed publications and one institutional report) published between 2023 and 2026 specifically address electric vehicles, autonomous delivery robots, drones, and shared urban infrastructure, the review organizes its findings into an explicit technology taxonomy and a comparative table spanning 16 representative studies, enabling a systematic cross-technology comparison. The study further develops a dedicated discussion section that confronts the identified trends with unresolved research gaps, together with a structured, thematically organized set of future research directions.

Several literature reviews already address individual facets of sustainable last-mile delivery electric vehicles [22], autonomous delivery robots [23], drones [24, 25], or collaborative business models for consolidation centers [26] but, to the best of the authors' knowledge, none simultaneously (i) applies a formal PRISMA protocol, (ii) spans all four technology families within a single taxonomy, and (iii) illustrates the resulting comparative analysis with dedicated charts linking each technology family to explicit comparison criteria. This positioning is what differentiates the present review from the single-technology reviews cited above, which typically address the smart-city concept and last-mile transport as loosely connected themes rather than as an integrated comparative framework. The smart-city generational framework (SC 1.0–5.0) is used in Section 2.1 as contextual background only; it is not a coding dimension of the taxonomy or of the comparative analysis, and its operationalization as an analytical lens is proposed as a future research direction (Section 6.2, direction E).

[1] This paper substantially extends prior exploratory, ROADEM'24 conference-stage work by the same authors on last-mile transport in smart cities. Relative to that earlier contribution, the present study adds more than 30% new content, including a formal PRISMA 2020 review methodology, an enlarged literature corpus (from 47 to 60 references), a restructured and criteria-based technology taxonomy illustrated with comparative charts, an entirely new discussion section, and a structured set of future research directions. The earlier ROADEM'24 contribution appeared in conference proceedings only and has not been published in a journal.

Based on this enlarged corpus, this review aims to (i) provide an updated and rigorous synthesis of the LM transport problem in smart cities, (ii) classify current and emerging technological and organizational solutions into a coherent, criteria-based comparative taxonomy, and (iii) identify open research avenues that can guide both academics and practitioners toward more sustainable LM systems. The remainder of the paper is organized as follows. Section 2 introduces the smart city background. Section 3 details the review methodology. Section 4 presents a comparative study of sustainable last-mile technologies, illustrated with comparative charts. Section 5 discusses the findings, cross-cutting research gaps, and the study's limitations. Section 6 concludes with a structured set of future research directions.

2. Background: The Smart City Concept

Due to organizational, cultural, and technological shifts, the concept of the SC has gained substantial traction over the past decade. A SC is generally understood as a city that has optimized its functioning across multiple domains, including governance and the provision of urban services, to support sustainable, pleasant, and environmentally friendly mobility for its population [10]. A widely cited definition characterizes a SC as a developed modern metropolis that uses ICTs and other technologies to enhance living standards, competitiveness, and the operational effectiveness of urban services, while guaranteeing resource availability for both current and future generations [27].

2.1. Characteristics and generations of the smart city

The SC is commonly described through four major attributes sustainability, intelligence, urbanization, and quality of life [15, 27] while government, economy, and infrastructure act as cross-cutting dimensions linking these attributes together. Sustainability addresses waste, pollution, energy, climate change, infrastructure, governance, and health; urbanization is measured through infrastructure, technology, governance, and economic indicators; quality of life reflects the mental and financial well-being of the population; and intelligence covers smart environments, smart living, smart mobility, smart governance, smart people, and smart economy. Smart mobility specifically requires ICT infrastructure together with safe, innovative, and sustainable transportation solutions, placing LM delivery squarely within the smart-mobility dimension of the SC.

The literature further describes the evolution of smart cities through five generations, from SC 1.0 (technology-driven, dominated by large technology suppliers such as Cisco and IBM) to SC 5.0 (a cooperative human–AI ecosystem capable of balancing the competing interests of multiple urban stakeholders in real time) [28, 29]. In SC 2.0, mayors and municipal councils replace technology vendors as the primary drivers of adoption, addressing pollution, sanitation, health, and transportation in collaboration with citizens, although citizen involvement in these informal decision-making structures often remains low. SC 3.0 marks a shift toward citizen- and user-driven demand, with government acting as a facilitator of public opinion within a connected ecosystem spanning IoT, 5G connectivity, smart transportation, energy and utilities, public health, and data analytics. SC 4.0 adds two further success factors a holistic integration approach and explicit recognition that the benefits of smart-city technologies are not necessarily distributed equally across all community members [30]. Generations SC 3.0 and SC 4.0 are of particular relevance to LM transport, as they mark the transition toward platformization and the integration of Industry 4.0 technologies including electric vehicles, 5G connectivity, and IoT-based urban services that underpin most of the technological solutions reviewed in Section 4. In this review, the SC 1.0–5.0 framework serves only to situate the smart-city concept; the four-family taxonomy of Section 4.3 and the comparative analysis of Section 4.5 are not organized by smart-city generation.

The smart-city literature increasingly combines technological concerns, such as AI and IoT, with research addressing the social and environmental dimensions of urban development, rather than its purely technological dimension alone (see the bibliometric overview in Section 4.1). This dual technological and social emphasis is directly reflected in the four-family technology taxonomy developed in Section 4.3 of this review, which explicitly separates purely technological solutions (EVs, ADRs, drones) from organizational and governance-oriented solutions (shared and collaborative infrastructure).

2.2. Why last-mile transport is a smart-mobility priority

The term "last mile" originated in the telecommunications industry to describe the final segment of a network; in supply chain contexts it denotes the last local warehouse, consolidation point, or distribution center before the final delivery to the customer [31]. Synonyms such as final-mile, home delivery, business-to-consumer (B2C) distribution, and grocery delivery are also common in the literature [32]. LM transport in smart cities remains a comparatively young and still-developing research area, involving multiple stakeholder groups (individuals, governments, shippers, receivers, and transport companies [12]). Scholars estimate that the logistics management phase of the supply chain, which accounts for roughly 28% of total delivery cost, is also the least efficient and least environmentally friendly stage [33, 34, 35, 36], which explains the intensity of recent research interest in the topic and motivates the systematic review conducted in this study.

3. Methodology

This study formalizes its review process according to the PRISMA 2020 statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [21], following established guidance for evidence-informed management research [37], rather than relying on an informal comparative reading of the literature. This section documents the review questions, search strategy, eligibility criteria, screening procedure, synthesis approach, and quality assessment.

3.1. Review questions

RQ1: How is the smart-city concept operationalized in relation to sustainable last-mile transportation in the literature?

RQ2: Which technological solutions (vehicles, autonomous systems, aerial systems) and organizational solutions (shared infrastructure, collaborative logistics) are proposed to reduce the externalities of last-mile delivery?

RQ3: What are the main research gaps and future research directions that emerge from the confrontation of these solutions with real-world implementation constraints?

3.2. Search strategy and databases

The search was conducted across Scopus, Web of Science, and Google Scholar, mirroring the databases most frequently used in comparable systematic reviews of last-mile and smart-city logistics [22, 24, 38, 39]. The search string combined three concept blocks using Boolean operators: (i) "smart city" OR "smart cities"; (ii) "last mile" OR "last-mile" OR "urban logistics" OR "urban freight"; and (iii) technology-specific terms "electric vehicle*", "autonomous delivery robot*", "drone*" OR "UAV", "cargo bike*", "micro-hub*" OR "consolidation center*". The search was run in two stages. An initial search, executed in March 2024, covered publications up to early 2024 and constituted the review's core corpus. An update search, executed in July 2026, covered publications from January 2023 to July 2026 in order to capture the most recent developments in EV, ADR, drone, and shared-infrastructure research. Because the two search windows overlap between January 2023 and early 2024, records retrieved by both searches were removed as duplicates. The 2025–2026 references of this review are published articles, chapters, or reports retrieved from publisher records at the time of the update search; none is an unpublished preprint.

3.3. Eligibility criteria

Studies were included if they were: (i) published in a peer-reviewed journal, edited book chapter, or indexed conference proceedings (or, exceptionally, an international-organization policy report); (ii) written in English or French; (iii) directly addressing last-mile transport, urban freight, or smart-city mobility; and (iv) published between 2001 and 2026, reflecting the emergence of both the smart-city and modern e-commerce logistics literature. Studies were excluded if they: (i) addressed passenger mobility exclusively without any freight or delivery component; (ii) were not accessible in full text; or (iii) were duplicate records across databases.

3.4. Study selection (PRISMA flow)

Figure 1 presents the PRISMA 2020 flow diagram summarizing the identification, screening, eligibility, and inclusion stages of the review.

Of the 1,284 records identified through the database searches, 972 were removed before screening, as duplicates (including records retrieved by both the initial and the update search) or because they fell outside the date, language, or document-type limits. The titles and abstracts of the remaining 312 records were screened against the eligibility criteria, and 216 were excluded because they did not address freight or last-mile delivery in an urban or smart-city context (for instance, studies limited to passenger mobility), or because they did not concern any of the four technology families or the organizational solutions examined in this review. The full texts of the remaining 96 reports were then assessed, and 38 were excluded because the full text was not accessible, because the study did not provide a sufficiently explicit link between a last-mile solution and the smart-city or urban-logistics context, or because it did not offer analytical or empirical content on the technology or organizational solution (e.g., purely descriptive or promotional documents). Fifty-eight studies were retained for the qualitative synthesis. Exclusion reasons were applied according to the eligibility criteria stated in Section 3.3, but were not tallied separately at each stage; this is acknowledged as a limitation of the reporting (Section 5.4).

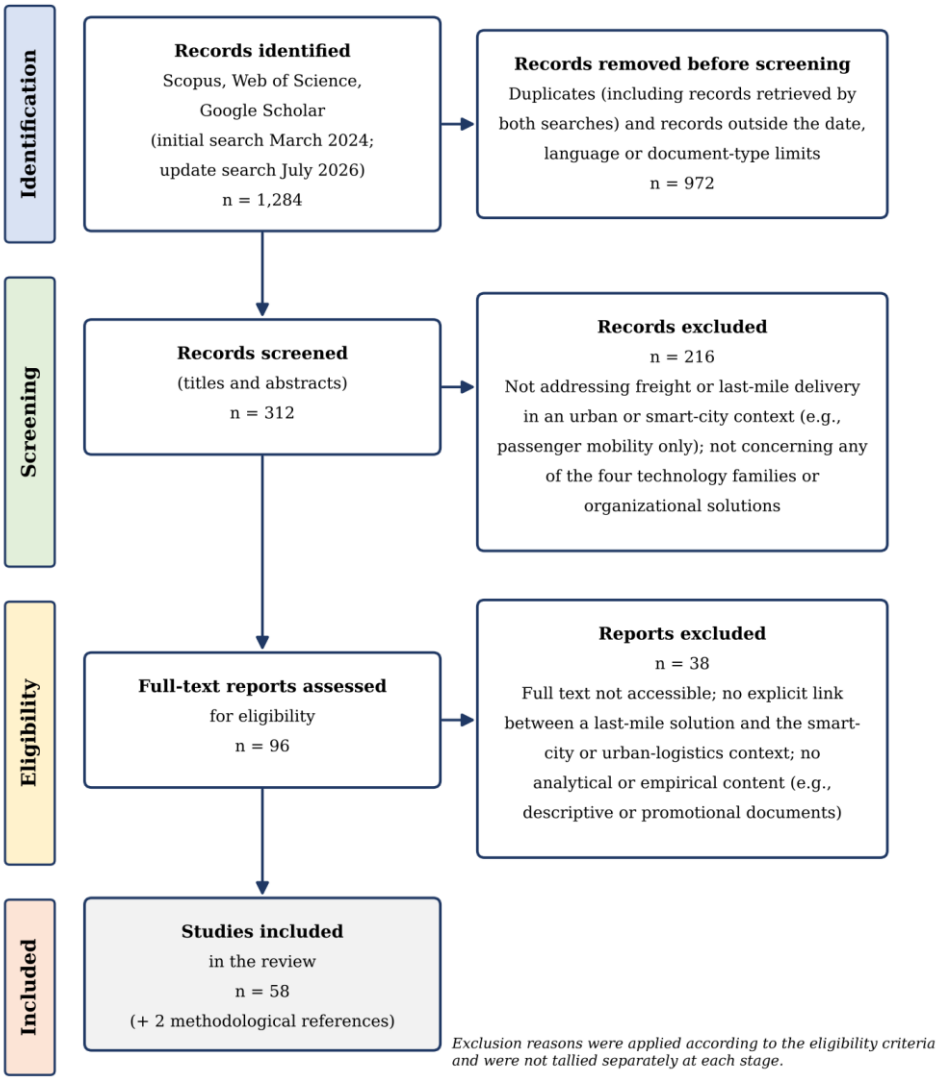

Figure 1. PRISMA 2020 flow diagram of the study selection process.

3.5. Data extraction and synthesis

For each included study, the following information was extracted: authors and year, main research topic, technology or organizational solution addressed, methodological approach, and where available reported quantitative outcomes (e.g., emission or vehicle-kilometer reductions). Data were synthesized narratively and organized into the technology taxonomy presented in Section 4.3, following the thematic categories that emerged inductively from the coding of the 58 included studies: (i) smart-city foundations, (ii) last-mile transport challenges, (iii) electric vehicles, (iv) autonomous delivery robots, (v) drones, and (vi) shared/collaborative infrastructure. Each study was assigned to a single technology family according to its primary emphasis, i.e., the solution that constitutes the main object of its research question or model; studies that combine or jointly review several families were coded as "Mixed / cross-cutting".

3.6. Quality assessment and corpus size

No formal risk-of-bias or critical-appraisal instrument (e.g., CASP or MMAT) was applied to the included studies. The corpus is deliberately heterogeneous (systematic, scoping, and bibliometric reviews, conceptual frameworks, optimization models, pilot-based case studies, and one institutional report), and the available appraisal instruments are designed for specific study designs and cannot be applied uniformly across such a mix. The quality of the evidence base was instead safeguarded by three pragmatic measures: (i) only peer-reviewed or institutionally published sources were eligible; (ii) full-text availability was required, so that each study could be coded on its methodology rather than on its abstract; and (iii) the study design of each included study (review or survey versus primary, empirical, or methodological research) was recorded during data extraction and is reported in Figure 5, so that the strength of the evidence behind each family can be read alongside the results. The absence of a formal appraisal is acknowledged as a limitation (Section 5.4).

The final corpus (58 included studies out of 1,284 records) reflects the scope of the review, which maps four technology families against a smart-city and last-mile context rather than exhaustively reviewing each family. For the technology-specific literature the review follows an overview-of-reviews logic: the most recent systematic, scoping, and bibliometric reviews of EVs, ADRs, drones, and shared infrastructure [22, 23, 24, 25, 38, 39, 40] are synthesized rather than re-reviewing the several hundred primary studies they cover (e.g., 307 articles in the review by Jazairy et al. [24] alone). All 1,284 records were screened and no sampling strategy was applied; studies were retained only when they met the full-text relevance criteria described above. This design choice limits the coverage of primary studies and is acknowledged in Section 5.4.

4. A Comparative Study of Sustainable Last-Mile Transportation Technologies

4.1. Bibliometric overview

A bibliometric search conducted on the Mendeley platform (query: "Last Mile and smart cities"; search of 22 November 2026) shows that the number of publications on last-mile delivery and smart cities remained relatively stable between 2020 and 2024, at 37 to 49 publications per year, before rising sharply in 2025 to 85 publications (Figure 2). The count for 2026 (71) is incomplete at the date of the search. This recent rise coincides with the rapid development of AI and IoT technologies, which offer unprecedented opportunities to transform city administration through real-time data collection, advanced analytics, and improved decision-making for urban infrastructure, mobility, and public services, and with a growing research interest in the social and environmental dimensions of smart cities, particularly solutions that improve social equity and quality of life while reducing the ecological footprint of urban areas, a trend that directly motivates the technology taxonomy developed in Section 4.3.

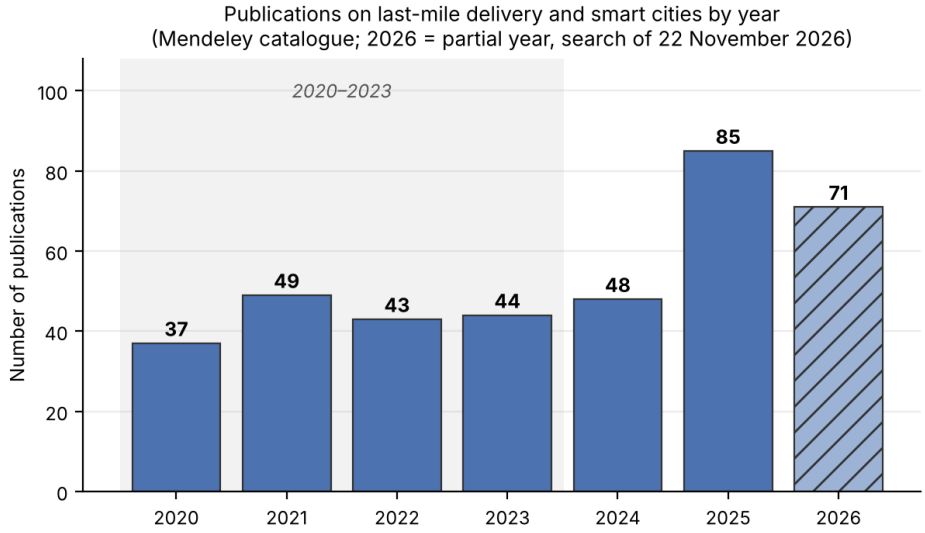

Figure 2. Number of publications retrieved by year for the query "Last Mile and smart cities" in the Mendeley catalogue (search of 22 November 2026; counts as displayed by the Mendeley year filter; 2026 is a partial year).

Table 1 summarizes representative studies illustrating the main technologies mobilized in smart-city research more broadly, from connected and autonomous vehicles to big-data analytics and IoT-based urban information systems. These seven studies are illustrative rather than exhaustive: each technological domain of smart-city research (connected vehicles, smart logistics, last-mile externalities, online retailing, energy, big-data analytics, and IoT) is represented once, and the study retained for each domain is the one that, in the authors' judgment, most directly links that domain to smart-city mobility or logistics. The selection thus reflects topical coverage rather than a systematic ranking (e.g., by citation counts).

Table 1. Main technologies used in smart-city research.

Authors	Main topics	Technologies
Campisi et al. [7]	Smart cities, connected and autonomous vehicles (CAVs), mobility patterns	CAVs, smart infrastructure
Kauf [41]	Smart logistics, smart-city development	Logistics optimization, supply chain management
Ranieri et al. [13]	Last-mile logistics, externalities cost reduction, sustainability	Logistics optimization, data analytics
Xiao et al. [31]	Online retailing, last-mile delivery, urban logistics	E-commerce, logistics networks
Calvillo et al. [10]	Energy management, smart cities, planning	Renewable energy sources, smart grids
Nathali et al. [42]	Smart cities, performance improvement, big-data analytics	Big data analytics, data mining
Jin et al. [43]	Smart city, Internet of Things (IoT), information frameworks	IoT sensors, data communication networks

4.2. Last-mile transport in smart cities: structural challenges

This transportation system involves three distinct groups of stakeholders: the supply side (producers, online retailers, and courier/express/parcel companies), the demand side (individual consumers, businesses, and institutions), and the physical environment, which falls under the jurisdiction of local government [44]. Because LM demand keeps growing alongside the expansion of smart cities, sustainable mobility planning requires the rational selection of distribution providers to raise efficiency and lower costs [45]. Since 1959, the Vehicle Routing Problem (VRP) the combinatorial core of most LM optimization models has been the subject of extensive research [46, 47, 48, 49, 50, 51], and the growth of e-commerce over the last two decades

has intensified the need for responsive omnichannel distribution [32, 52]. Multimodality and flexibility in transportation networks are expected to keep increasing [53], and several authors emphasize the benefits of integrating client pick-up and home delivery within a single, simultaneous operational model [54, 55].

4.3. A technology taxonomy of sustainable last-mile solutions

Building on the enlarged corpus of 60 references, this subsection organizes the reviewed technological and organizational solutions into four families, moving beyond a purely vehicle-centric perspective to also capture robotic, aerial, and organizational solutions.

4.3.1. Electric vehicles (EVs)

Electric vehicles remain the most extensively studied technological lever for reducing the environmental footprint of LM delivery, spanning routing problems with charging constraints [34, 47, 51, 56] to fleet-level bibliometric syntheses. A recent bibliometric review covering the 2013–2024 period confirms that research on EVs in LM delivery has concentrated on battery technologies, smart-grid integration, and carbon-emission control, with the USA identified as a leading research hub [22]. Despite this maturity, EV adoption in commercial fleets continues to be constrained by high upfront capital costs, limited charging infrastructure, and, as shown in recent collaborative-logistics pilots, pricing tensions between electric and conventional fleet operators sharing the same consolidation infrastructure [26].

4.3.2. Autonomous delivery robots (ADRs)

Sidewalk-based autonomous delivery robots have moved from prototype testing to early commercial deployment in several cities since 2023, prompting a rapidly growing academic literature. A dedicated literature review of ADRs highlights their potential to reduce road congestion and vehicle-related externalities, while also cautioning that the externality may partly relocate to sidewalks, raising new pedestrian-safety and public-space-sharing questions [23]. Although operationally promising, ADRs remain limited to lightweight, short-distance parcels, and their efficiency is closely tied to sidewalk infrastructure quality, reinforcing the need to consider them as a complement to, rather than a substitute for, vehicle-based delivery.

4.3.3. Drones (UAVs)

Unmanned aerial vehicles constitute the most technologically disruptive but also most regulation-constrained LM solution reviewed in this study. A systematic literature review of drone-based LM delivery, synthesizing 307 interdisciplinary articles, maps the potential, challenges, and solutions of drone delivery across four stakeholder groups (senders, receivers, regulators, and society) [24]. Complementary technical reviews emphasize that most current barriers are not purely technological but relate to regulatory fragmentation, airspace management, and infrastructure needs for take-off and landing in dense urban environments [25]. These findings suggest that drones are currently best suited to niche applications (e.g., urgent, lightweight, or medically critical shipments) rather than to mainstream urban parcel delivery. The potential of drones for last-mile logistics had already been explored, together with 3D printing, in an early exploratory study [57].

4.3.4. Shared and collaborative infrastructure

A fourth and increasingly prominent family of solutions relies not on a specific vehicle technology but on the organizational redesign of urban logistics through shared infrastructure. Cargo bikes combined with mobile parcel lockers have been studied as an integrated routing and location-planning problem [58], while urban logistics hubs increasingly multifunctional spaces offering charging, rest, and even light repair facilities are the subject of a dedicated international roundtable report emphasizing their role as neutral, shared assets for multiple carriers [59]. More broadly, home-delivery-oriented reviews of Industry 4.0 technologies show that AI, IoT, and automation are typically deployed in combination with, rather than as a replacement for, these organizational innovations [60]. Recent reviews synthesizing sustainable ground-based LM delivery from an operations-research perspective [38], and scoping reviews proposing conceptual frameworks for smart and sustainable LM systems [39], both converge on the conclusion that shared infrastructure and collaborative governance are pre-conditions for the environmental gains promised by EVs, ADRs, and drones to materialize at scale.

Table 2 presents a substantially enlarged taxonomy table covering all four technology families, drawing on 16 representative studies of the corpus. A study was considered representative when (i) it belongs to the 58

included studies, (ii) its primary object is one of the four families (or an explicit synthesis across them) as a solution for urban or last-mile distribution, including the routing models that support it, and (iii) it serves as an anchor reference in the discussion of Sections 4.3, 4.4, or 5. Among the studies meeting these conditions, the 16 retained are those that most directly document the technology or organizational solution itself. The remaining 42 included studies address smart-city foundations, generic last-mile challenges, or generic routing and supply-chain topics, and are used as background, which is why they are not tabulated. Each study is assigned to a single family according to its primary emphasis (Section 3.5); studies that combine or jointly review several families are labeled "Mixed".

Table 2. Extended taxonomy of sustainable last-mile technologies and organizational solutions. Each study is assigned to a single family according to its primary emphasis; "Mixed" denotes studies that combine or jointly review several families.

Authors	Main topic	Technology / solution family
Fan et al. [56]	Time-dependent multi-depot green VRP with time windows	Electric vehicles
Xiao & Konak [51]	Heterogeneous green VRP with time-varying congestion	Electric & alternative-fuel vehicles
Sassi et al. [47]	VRP with mixed conventional/heterogeneous EV fleet, time-dependent charging costs	Electric vehicles
Erdoğan & Miller-Hooks [34]	Green Vehicle Routing Problem	Electric & alternative-fuel vehicles
Luke [22]	Bibliometric review of EVs in last-mile delivery (2013–2024)	Electric vehicles
Apanasevic & Fjällström [26]	Collaborative business model for EV/conventional freight consolidation centres	Shared infrastructure (also addresses EVs)
McKinnon [57]	Possible impact of 3D printing and drones on last-mile logistics	Drones
Jazairy et al. [24]	Systematic review of drones in last-mile delivery (307 studies)	Drones / UAV
Sorbelli [25]	UAV-based delivery systems: trends and research challenges	Drones / UAV
Alverhed et al. [23]	Literature review of autonomous last-mile delivery robots	Autonomous delivery robots
Rolf et al. [58]	Route and location planning for cargo bikes and mobile parcel lockers	Cargo bikes, shared lockers
International Transport Forum [59]	Urban logistics hubs: roundtable synthesis	Shared infrastructure / micro-hubs
Tadić et al. [60]	Application of Industry 4.0 technologies in home delivery	Mixed (AI, IoT, automation)
Moradi et al. [38]	Systematic review of sustainable ground-based LM delivery	Mixed / operations-research perspective
Moufad et al. [39]	Scoping review and conceptual framework for smart, sustainable LM systems	Mixed / conceptual framework
Corvello et al. [40]	City Logistics 4.0: reconceptualization and research agenda	Mixed / collaborative logistics

4.4. Organizational and collaborative models

Beyond the vehicle- and robot-centric technologies discussed above, the enlarged corpus reveals a distinct and growing stream of research on the organizational architecture of last-mile logistics. Three organizational models recur across the reviewed studies. The first is the urban consolidation center (UCC), a logistics facility that decouples long-distance transport from last-mile distribution and enables multiple shippers to pool freight before final delivery using low-emission vehicles [26, 59]. The second is the collaborative business model, in which competing or complementary logistics service providers jointly plan routes, share vehicle capacity, or co-invest in shared assets; recent empirical work on a Swedish freight-consolidation pilot documents an 88% reduction in last-mile delivery trips once inbound shipments were consolidated, illustrating the magnitude of

the efficiency gains achievable through this model, while also cataloguing recurring implementation barriers such as data-sharing reluctance, IT-system fragmentation, and pricing disagreements between electric- and conventional-fleet operators [26]. The third is the platform-based coordination model, in which digital platforms match freight demand with available capacity across multiple carriers, extending the logic of the sharing economy to urban freight.

Taken together, these organizational models suggest that the environmental and operational benefits attributed to EVs, ADRs, and drones in Sections 4.3.1–4.3.3 are, in practice, conditional on the surrounding organizational architecture: a fleet of electric vans operating in a fragmented, uncoordinated market captures only a fraction of the emissions and congestion benefits that the same fleet could achieve within a well-governed, collaborative consolidation scheme [26, 59, 60]. This observation motivates the cross-cutting discussion developed in Section 5.

4.5. Comparative Charts and Criteria-Based Analysis

To move from a purely narrative taxonomy to a genuine comparative study, and directly in response to RQ2 ("Which technological solutions ... are proposed to reduce the externalities of last-mile delivery?"), the 16 studies summarized in Table 2 and the broader 60-reference corpus are further analyzed here against three explicit comparison criteria: (i) the distribution of research effort across the four technology families, (ii) the qualitative maturity of each family against four RQ2-derived sub-criteria (technological maturity, cost-effectiveness, environmental impact potential, and regulatory/infrastructure readiness); and (iii) the balance between review-type and primary research studies underpinning the corpus, which speaks to the robustness of the evidence base and to RQ3 on remaining research gaps.

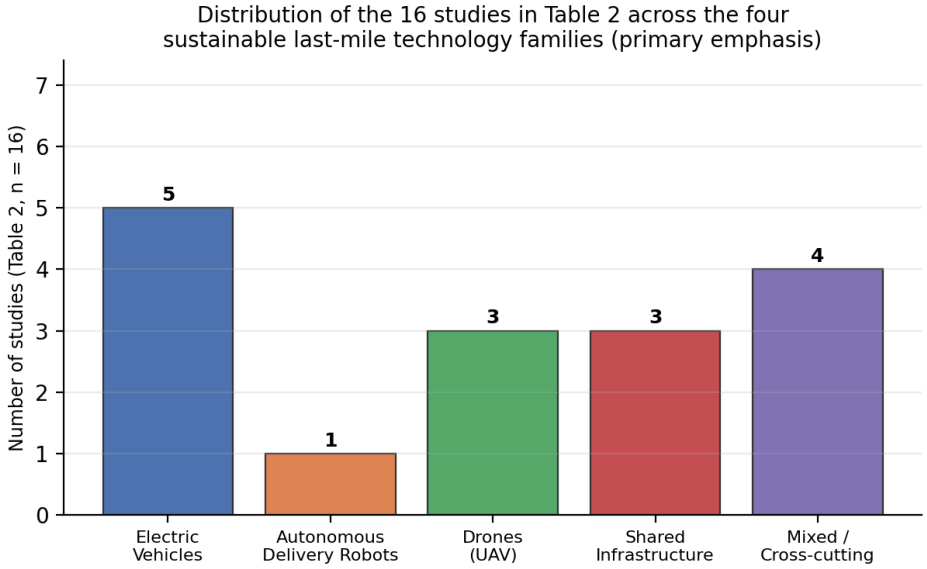

Figure 3. Distribution of the 16 studies in Table 2 across the four sustainable last-mile technology families. Studies are assigned by primary emphasis; "Mixed / Cross-cutting" denotes studies combining several families.

Figure 3 confirms the electric-vehicle bias already visible in the narrative review of Section 4.3.1: five of the sixteen representative studies (31.3%) address EVs, compared with only one dedicated specifically to ADRs. This imbalance is itself an analytical finding relevant to RQ3: it suggests that autonomous delivery robots remain comparatively under-theorized in the peer-reviewed literature relative to their fast-growing commercial deployment noted in Section 4.3.2, making ADR-specific modelling an area where research supply currently lags practical demand.

Figure 3 is deliberately restricted to the 16 studies of Table 2, i.e., those that can be assigned to one of the four technology families (or to an explicit cross-family synthesis) on the basis of their primary object. The other 42 included studies address smart-city foundations, generic last-mile challenges, or generic routing and supply-chain topics that belong to none of the four families; counting them would blur rather than complete

the picture. Figure 3 should therefore be read as the distribution of research effort within the technology-specific core of the corpus, not within the entire corpus; Figure 5, by contrast, covers all 58 domain-specific references. This restriction is acknowledged in Section 5.4.

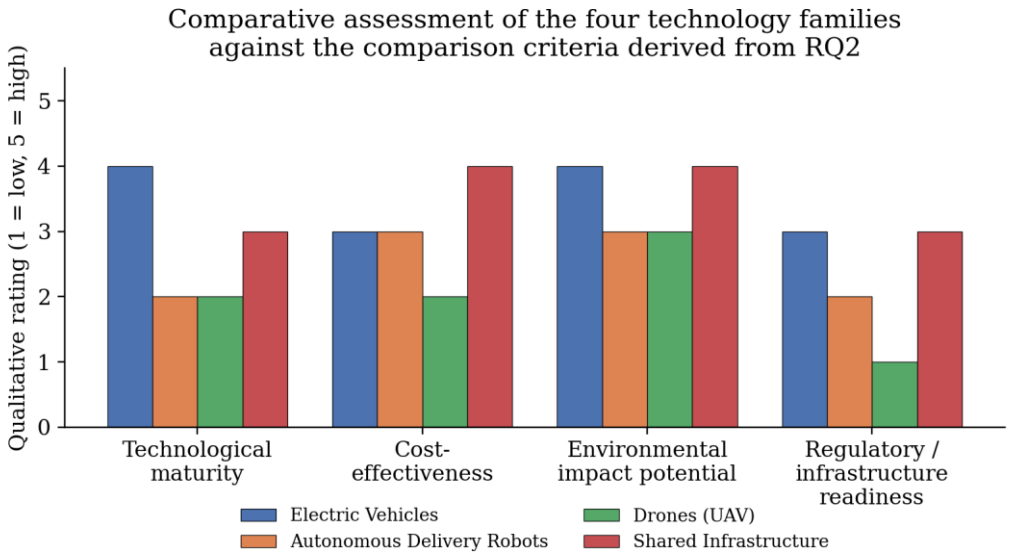

Figure 4. Comparative assessment of the four technology families against the RQ2-derived comparison criteria (qualitative ratings, 1 = low, 5 = high, derived from the qualitative synthesis in Sections 4.3.1–4.3.4). Ratings are assigned by the authors (see text for the scoring procedure).

The ratings of Figure 4 are a qualitative, author-assigned synthesis; they are not weighted averages of values extracted from the 58 studies, and no inter-coder reliability statistic is reported. The ratings were assigned by the authors on a 1–5 ordinal scale, on the basis of the evidence summarized in Sections 4.3.1–4.3.4; no external experts were consulted. The scale is interpreted as follows. Technological maturity: 1 = prototype or laboratory stage, 3 = pilots and early commercial use, 5 = widespread commercial deployment. Cost-effectiveness: 1 = costs clearly above conventional delivery with no documented offsetting gains, 5 = documented cost savings relative to conventional delivery. Environmental impact potential: 1 = negligible or uncertain benefit, 5 = large documented reductions in emissions, vehicle-kilometers, or trips. Regulatory and infrastructure readiness: 1 = restrictive or fragmented regulation and missing infrastructure, 5 = established regulation and infrastructure. Because the ratings are subjective, they should be read as an ordinal, hypothesis-generating summary of the narrative evidence rather than as measured values, and their robustness should be tested in future work (e.g., through a structured expert panel).

Figure 4 makes explicit the trade-offs that remain implicit in a purely narrative taxonomy. Electric vehicles score highest on technological maturity and environmental impact potential but only moderately on cost-effectiveness, reflecting the high upfront capital costs discussed in Section 4.3.1. Shared infrastructure scores highest overall, combining strong cost-effectiveness and environmental impact with moderate maturity, which is consistent with the discussion in Section 4.4 identifying organizational architecture as a precondition for the other three families to deliver their full benefits. Drones score lowest on regulatory and infrastructure readiness, consistent with the regulatory-fragmentation barrier identified in Section 4.3.3, while ADRs occupy an intermediate position across all four criteria, reflecting their status as an early-commercial-deployment technology with a comparatively thin peer-reviewed evidence base, as shown in Figure 3.

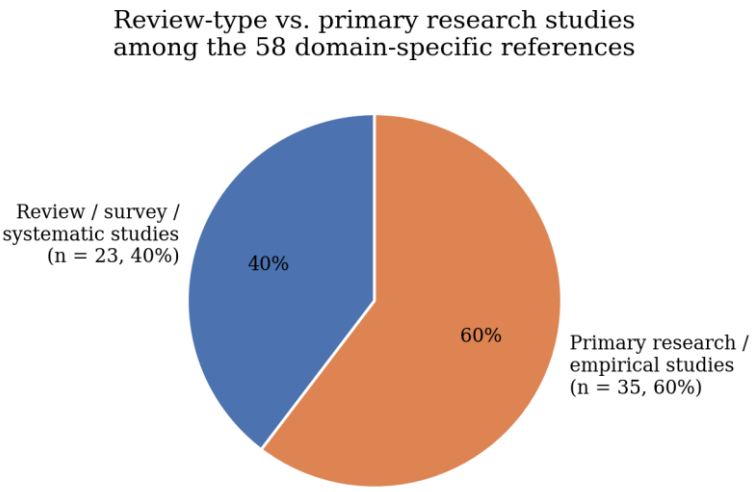

Figure 5. Balance between review-type (survey, systematic review, scoping review, bibliometric review) and primary research studies among the 58 domain-specific references of this study (two methodological references on review protocols are excluded from this count; 58 + 2 = 60 references in total).

Figure 5 shows that 23 of the 58 domain-specific references (40%) are themselves review, survey, or bibliometric studies, while 35 (60%) report primary, empirical, or methodological research. This balance is analytically important for two reasons. First, a substantial review-type share indicates that the present synthesis is grounded not only in individual primary studies but also in prior secondary syntheses of sub-topics such as green vehicle routing [33, 36], smart-city architectures [27, 28], and last-mile logistics innovation [12, 13, 32], which strengthens the evidentiary basis of the taxonomy developed in Section 4.3 and partially validates its structure against independent prior classifications. Second, the concentration of review-type studies among the most recent additions to the corpus (seven of the eleven 2023–2026 references are themselves systematic or scoping reviews [22, 23, 24, 25, 38, 39, 40]) signals that several of the four technology families are reaching a stage of research maturity where secondary synthesis becomes both possible and valuable, a pattern consistent with the technological-maturity ratings reported in Figure 4 for EVs and shared infrastructure, and with the comparatively thinner review-type coverage of ADRs noted above.

5. Discussion

5.1. Cross-cutting trends

Three cross-cutting trends emerge from the confrontation of the 58 included studies. First, the technological maturity of the four solution families is markedly uneven: EVs are the most operationally mature but remain economically constrained; ADRs are entering early commercial deployment but face public-space governance questions; drones remain largely confined to regulatory-sheltered niches; and shared infrastructure, while conceptually mature, depends on collaborative governance arrangements that are difficult to sustain once public funding ends [26, 59]. Second, none of the reviewed studies proposes a single dominant solution; instead, hybrid configurations combining EVs, cargo bikes, and consolidation centers consistently outperform single-technology approaches in the empirical and simulation-based studies reviewed [26, 38, 39]. Third, organizational and governance barriers, rather than purely technical ones, recur as the most frequently cited obstacle across all four families, including data-sharing reluctance, misaligned incentives between public and private actors, and the absence of durable business models once pilot funding is withdrawn [26, 59, 60].

5.2. From Isolated Technologies to Integrated Systems

This review confirms a well-established externalities framework (air pollution, noise, congestion, accidents, land use, infrastructure wear, and energy dependence) while substantially refining the technological landscape used to address it. Whereas early exploratory work in this field tended to treat EVs, drones, and cooperative

logistics as separate, loosely connected themes, the enlarged corpus assembled here makes clear that these are increasingly studied as complementary components of integrated last-mile systems, and that the organizational dimension (governance, business models, data integration) has become at least as important a research theme as the underlying vehicle or robotic technology itself [26, 40].

5.3. Research gaps

- Methodological gap: Few studies combine quantitative routing/optimization models with empirical, pilot-based evidence; most either simulate technology performance or report qualitative pilot findings, but rarely both [26, 38].
- Integration gap: The literature on EVs, ADRs, and drones remains largely siloed by technology family; systematic comparative evaluations of mixed fleets (e.g., EV + ADR + cargo bike) under identical urban scenarios are scarce.
- Governance gap: Business-model and governance frameworks for shared infrastructure (consolidation centers, micro-hubs) are still emergent and have rarely been tested beyond small-scale, publicly funded pilots [26, 59].
- Equity gap: The distributive effects of last-mile innovations (e.g., who bears the cost of the transition to greener but more expensive fleets) remain under-examined, despite being explicitly raised in recent pilot studies [26].
- Regulatory gap: Drone and ADR deployment in dense urban areas continues to be constrained by fragmented, jurisdiction-specific regulation, which is rarely modelled explicitly in optimization-oriented studies [24, 25].

5.4. Limitations of the review

This review has five main limitations. First, although the search strategy followed a documented PRISMA protocol, the underlying database coverage (Scopus, Web of Science, Google Scholar) may under-represent grey literature such as municipal reports and industry white papers, which are particularly relevant for fast-moving fields such as ADR and drone commercial deployment. Second, the technology taxonomy in Section 4.3, while systematically derived from the coded corpus, inevitably simplifies the boundaries between categories: several reviewed studies (e.g., [26, 38, 40, 60]) explicitly combine two or more technology families, and were classified according to their primary emphasis rather than an exhaustive multi-label scheme (for instance, the study by Apanasevic and Fjällström [26] addresses electric and conventional fleets within a consolidation-centre business model and is classified under shared infrastructure). Third, because the field is evolving rapidly, some of the quantitative findings reported in very recent sources (2025–2026) reflect early-stage pilots rather than mature, generalizable deployments, and should be interpreted with corresponding caution. Fourth, no formal quality or risk-of-bias appraisal was performed and the corpus of 58 studies is restricted by design (Section 3.6), the exclusion reasons at each screening stage were not tallied separately (Section 3.4), and Figure 3 covers only the 16 studies of Table 2. Fifth, the ratings of Figure 4 are subjective, author-assigned judgments whose inter-rater reliability was not tested (Section 4.5).

5.5. Practical implications

For city planners and logistics practitioners, three practical implications follow from this review. First, technology procurement decisions for last-mile delivery should not be made in isolation from infrastructure and governance planning: a municipality investing in EV incentives without also supporting shared consolidation infrastructure is likely to capture only partial benefits, as documented in the Gothenburg pilot study [26]. Second, pilot projects for ADRs, drones, or consolidation centers should be designed from the outset with a post-pilot sustainability plan, given the recurrent finding that many EU-funded urban consolidation initiatives ceased operating once public funding ended [59]. Third, logistics service providers considering the adoption of electric fleets should anticipate the pricing and cost-sharing tensions that arise when electric and conventional vehicles coexist within the same collaborative scheme, and should negotiate pricing and incentive mechanisms explicitly at the outset of any collaboration [26].

6. Conclusion and Future Directions

6.1. Conclusion

This study has provided a rigorous, PRISMA-based overview of the many issues raised by sustainability in relation to last-mile transport in smart cities. By formalizing the review methodology, enlarging the literature corpus to 60 references, and reorganizing the findings into an explicit, criteria-based technology taxonomy illustrated with comparative charts, this review offers an actionable synthesis of a fast-moving field. Urban transportation continues to generate a wide array of externalities air pollution from vehicle emissions, noise pollution, accidents, congestion, land use, infrastructure wear, and energy dependence and the dual challenge of meeting global-trade demand while respecting environmental standards remains central to last-mile logistics research.

The taxonomy developed in Section 4.3 shows that innovation capable of reducing these externalities spans four complementary families' electric vehicles, autonomous delivery robots, drones, and shared/collaborative infrastructure each with distinct advantages, limitations, and maturity levels, as summarized by the comparative charts of Section 4.5. For smart cities to effectively tackle the last-mile transport problem, innovative thinking is required not only at the technological level but, just as importantly, at the organizational and governance level. The rise of express shipments, driven by e-commerce growth, new ICT, and the Industry 4.0 paradigm, requires a reevaluation of how goods move through cities, while the massive data flows generated by connected devices, infrastructure, and vehicles must be translated into workable governance structures. Reducing the externalities of last-mile delivery one of the central objectives of any smart city will ultimately depend on the joint commitment of all stakeholders and the practical implementation of the collaborative, hybrid, and equity-aware solutions identified in this review.

6.2. Future Research Directions

Based on the research gaps identified in Section 5.3, this review proposes the following structured set of future research directions for sustainable last-mile transportation in smart cities.

(A) Integrated fleet modelling: develop routing and location models that jointly optimize hybrid fleets (EVs, ADRs, cargo bikes, drones) under shared infrastructure constraints, rather than studying each technology in isolation. Such models should explicitly represent transfer points between modes (e.g., van-to-robot or van-to-locker handoffs) to capture the efficiency gains and coordination costs that purely single-mode formulations cannot reveal.

(B) Empirically grounded business models: extend collaborative business-model frameworks such as those recently proposed for freight consolidation centers [26] to a wider range of urban contexts and stakeholder configurations, with longitudinal evaluation beyond the pilot phase. Particular attention should be paid to the post-funding sustainability of these schemes, given the recurrent finding that publicly funded consolidation pilots frequently cease operating once initial grants expire [59].

(C) Equity-aware evaluation frameworks: design evaluation metrics for last-mile innovations that explicitly incorporate distributive effects (who pays, who benefits) alongside efficiency and emissions metrics, extending current cost–benefit approaches that focus almost exclusively on aggregate efficiency gains.

(D) Regulatory-aware optimization: incorporate regulatory and airspace/sidewalk-sharing constraints directly into ADR and drone routing models, rather than treating regulation as an exogenous, post-hoc consideration; this would allow researchers to quantify the efficiency cost of current regulatory fragmentation rather than assuming an idealized, unconstrained operating environment.

(E) Cross-city comparative studies: conduct systematic comparative studies across smart cities at different generational stages (SC 1.0 to SC 5.0) to assess how governance maturity moderates the effectiveness of last-mile technologies, an angle almost entirely absent from the reviewed corpus despite its direct relevance to technology-transfer and replication decisions faced by city planners.

(F) Longitudinal and multi-city bibliometric monitoring: extend the review-versus-research bibliometric split introduced in Section 4.5 into a longitudinal tracking exercise, to detect early when a technology family shifts from an exploratory, review-dominated stage toward a more mature, empirically validated one.

Taken together, these six directions suggest that the next generation of research on sustainable last-mile transportation will need to move beyond single-technology evaluation toward integrated, equity-aware, and empirically grounded decision frameworks a shift that this comparative review is intended to help initiate.

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All Authors contributed to this work and the revision of this paper, and approved the final manuscript.

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