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Parcel locker solutions for last mile delivery: a systematic literature review and future research directions

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The rapid growth of online shopping has increased customer demand for efficient logistics and last mile delivery. Parcel lockers (PLs) offer a promising solution by integrating digital technology with secure parcel handling, reducing delivery bottlenecks and traffic congestion while optimizing personnel utilization and improving efficiency. We conduct a systematic review of the literature on PL research, with a particular focus on its impact on cost reduction, operational efficiency, and sustainability. Most existing research on PL networks is heavily concentrated on determining optimal locations and developing efficient routing strategies. That said, some scholars have also explored other operational challenges, such as incorporating dynamic factors and diverse delivery capabilities into PL systems. This study identifies research gaps, such as the lack of empirical studies on mobile PLs and their integration with other urban logistics systems, and offers directions for future research. These findings contribute to understanding the potential of PL systems in advancing more efficient and sustainable last mile delivery solutions.

KEYWORDS
parcel locker, last mile delivery, sustainability, AI technology, systematic literature review

1 Introduction

Logistics service providers (LSPs) are at the forefront of innovative services ranging from instant delivery to next-day delivery, with challenges particularly focused on the last mile delivery phase. The last mile delivery problem, which is the final distance for goods from the delivery center to the customer's hands, is often considered the most challenging and resource-intensive stage [see, e.g., Suguna et al. (2021), Demir et al. (2022)]. It presents complex challenges, such as higher cost (Olsson et al., 2019), strict time restrictions (Ghilas et al., 2016), efficiency bottlenecks (Liu et al., 2020), traffic congestion [see, e.g., Li et al. (2021), Liu et al. (2023)], parking space requirement (Savelsbergh and Van Woensel, 2016), and various environmental issues (Ranieri et al., 2018). To reduce the complexity of last mile delivery on both customers and LSPs, researchers focus on new technological innovations and solutions, including network optimization (Deutsch and Golany, 2018), drone delivery [see, e.g., Chen et al. (2025), Bakach et al. (2022)], autonomous driving technology (Sorooshian et al., 2022), and integration with other transport capacities from different resources (e.g., crowdsourcing) [see, e.g., Ghaderi et al. (2022), Stokkink et al. (2024)].

In recent years, parcel lockers (PLs) have attracted significant interest from both academics and practitioners, reflecting their increasing strategic importance in addressing last mile delivery challenges. PLs have become central to urban logistics and sustainability discussions and frequently appear on policy agendas worldwide, particularly in densely populated regions. Despite this growing attention, considerable debate persists in the existing literature on the actual operational benefits, environmental effectiveness, and user acceptance of these technologies. Several studies demonstrate clear benefits, including reduced operational costs, decreased emissions, and improved delivery reliability. In contrast, others highlight potential drawbacks, such as underutilization and increased vehicle miles in sparsely populated areas. Such contradictions underscore the need for a comprehensive synthesis of existing research to clarify these uncertainties and inform future investigations. Thus, gaining insight into these dynamics can offer valuable perspectives for both practical applications and theoretical development in logistics.

PLs have emerged as a key innovation that has transformed the storage and retrieval of securely packaged parcels within specified size limits. The concept of PLs can be traced back to Asia nearly 2 decades ago (Tang et al., 2021), and it has undergone a remarkable evolution to the current intelligent and multifaceted system. PLs meet the changing needs of users by capturing the features of modern logistics by combining digital technologies with secure delivery mechanisms. PLs also expand their utility beyond traditional delivery services, including cold chain logistics, payment collection, and return handling. Over the years, the types of PLs have also evolved, including stationary, mobile (Peppel and Spinler, 2022), and autonomous mobile variants (Orenstein et al., 2019). From a service interaction perspective, PLs can also be classified as attended and non-attended systems. Attended lockers require interaction with service personnel at a designated pickup location, such as retail counters or postal agencies [e.g., (Niemeijer and Buijs, 2023; Corejova et al., 2022; El Moussaoui et al., 2022; Liu et al., 2021)]. In contrast, unattended lockers, such as APLs, enable fully self-service operations, often accessible 24/7 (Lagorio and Pinto, 2020). Despite their operational and behavioral implications, comparative research between these two service models remains scarce in the existing literature. By improving package delivery efficiency, reducing operational costs, and providing consumers with more flexible package retrieval options, PLs become an important service to reduce delivery failures, minimize package theft (or damage), and ultimately improve service standards and customer satisfaction in the logistics sector (Du and Wang, 2022). Additionally, these systems play a crucial role in reducing greenhouse gas (GHG) emissions and urban traffic congestion.

The first modern application of PL technology was introduced in Germany in the early 2000s by Deutsche Post DHL, called 'Packstation' (Niederprüm and van Lienden, 2021). This was followed by France in 2005 and gradually spread to other parts of Europe. A similar automated package delivery system entered the US and UK markets in early 2006. In 2011, major Chinese logistics companies, such as Cainiao Network, Hive, and ZTO Express, started adopting this technology in their networks (Smiota, 2022). In 2015, PL technology was promoted throughout the world, especially in large cities in Asia and Europe (DHL, 2023). In recent years, PLs have undergone significant improvements in terms of design and features. Their new designs and features make collecting or returning packages safer and easier. For example, new models use solar energy (DHL, 2023), showing that they can work well in different locations and aim to provide users with a better experience. These ongoing improvements mean that PL technology is becoming more practical and can be better incorporated into delivery networks.

Given the increasing importance and applicability of PLs in last mile delivery, it is important to understand and comprehensively assess their impact. To guide the structure and analysis of this review, we draw upon established constructs in last mile logistics theory. The last mile is recognized as the most complex and cost-intensive segment of delivery logistics, often evaluated through three critical lenses: operational efficiency, sustainability impact, and technological adaptability (Lim et al., 2016). We integrate this with the Triple Bottom Line (TBL) framework (Elkington and Rowlands, 1999), which conceptualizes sustainable logistics as balancing economic, environmental, and social objectives. These frameworks justify the three cornerstones of our review: operational challenges, sustainability impact, and AI-enabled innovation in parcel locker systems. This research highlights the need for a comprehensive literature review to describe current developments and outline future directions for studies. Therefore, the contributions of this research are threefold: (*i*) mapping an overview of the current research landscape of PLs; (*ii*) exploring the similarities and gaps between academic research and practical application of PLs; and (*iii*) identifying the research gaps that lay the groundwork for future investigations into innovative PL solutions. This paper is structured as follows. Section 2 introduces the research methodology, providing details on the systematic literature review. Sections 3–5 present the findings of the descriptive and thematic analyses. Given the descriptive and thematic analyses, research gaps are found and future research directions are summarized in Section 6. And finally, Section 7 provides the concluding remarks.

2 Review methodology

This section outlines the steps of a systematic literature review, following the PRISMA guidelines, which enhance clarity by defining research questions, assessing a broad literature base, and establishing inclusion and exclusion criteria. Meta-analysis within PRISMA can provide a comprehensive view by integrating data from multiple studies. Our study employs a systematic review approach based on evidence for PLs and follows the six-step process outlined by Durach et al. (2017) to ensure the reproducibility of the research methodology.

The first step in conducting a systematic review is formulating the research questions. The research questions are formulated as follows. (*RQ*1) What specific operational problems related to PLs are being analyzed? (*RQ*2) What are the sustainability impacts of PLs on last mile delivery? and (*RQ*3) What artificial intelligence technologies can be utilized in PL solutions? In the second step, the potentially relevant literature is identified by developing inclusion and exclusion criteria for the main characteristics of the study. In the third step, search engines and strings were selected. The study opted for four databases with extensive coverage of the relevant peer-reviewed literature, including Emerald Insight, Scopus, Web of Science, and ScienceDirect. In this study, Scopus was selected as the primary database for its wide coverage and strong analytical tools, making it ideal for bibliometric analysis. While ScienceDirect offers full-text access mainly to Elsevier publications, it also includes content from selected smaller publishers. However, Scopus provides broader indexing and advanced search features essential for systematic reviews. Keywords were combined to form a series of strings for use in database searches. Since the study focus is on PL solutions for last mile delivery, the search strings are specifically designed to select relevant papers for overlap between PL and last mile delivery. The time frame for the literature search was set from January 2017 to March 2025. This period captures the most recent advancements in PL technologies and last mile delivery strategies, particularly following the rapid digitalization and e-commerce growth during and after the COVID-19 pandemic. The chosen window allows the review to reflect both pre-pandemic foundations and post-pandemic innovations in PL systems. During this process, there are no restrictions on journals, disciplines, or publication dates, provided that the search strings are applied to the title, abstract, and keyword fields.

> (“locker” OR “parcel locker” OR “smart locker”) and (“last mile delivery” OR “city logistics” OR “urban logistics” OR “urbanisation” OR “innovation” OR “operations research” OR “transport*” OR “supply chain operation”)

The first search was conducted without criteria restrictions, resulting in a total of 4,717 items, including 211 in Emerald Insight, 665 in Scopus, 717 in Web of Science, and 3,124 in ScienceDirect. After the first search stage, an initial search was performed as the fourth step. This search included the removal of duplicates, non-journal articles, and articles outside the specified time range. In total, 1,768 relevant articles were identified. To achieve an acceptable level of precision and reduce subject bias in applying the inclusion/exclusion criteria (Step 2), two investigators performed a double screening process to verify reliability throughout the process as the fourth step. They independently performed preliminary and full-text screenings and then recorded decisions at each screening round. The selection of articles was checked against the criteria, then the results were compared and discussed, and finally the disagreements were resolved as they arose (Toorajipour et al., 2021). Articles that met the preliminary screening criteria entered the full-text screening stage. At this stage, the researchers conducted a detailed review of the full text to verify whether the inclusion criteria were met, while also excluding articles that did not meet the requirements. The number of articles selected for analysis and synthesis was reduced to 86 after applying the consensus criteria. In the fifth step, the articles were analyzed and synthesized after choosing the most relevant studies. Based on the purpose of analysis and synthesis, the methodology integrated quantitative and qualitative components (Denyer and Tranfield, 2009). The results of this study are then presented in the form of tabulations and discussion in the following three sections.

3 Findings from descriptive analysis

This section presents the descriptive analysis of the reviewed publications.

3.1 Descriptive profile of the literature

To provide a comprehensive overview, Figure 1 summarizes the descriptive profile of the literature across four dimensions: publication years, geographic distribution of studies, co-citation relationships among authors, and distribution of research methods. To gain insight into the development of PL research over time, an analysis is performed to explore the years of publication of journal articles during the literature review period. According to subfigure (a), all articles were published between January 2017 and March 2025. Most of the identified articles are quite recent, as 20 were published in 2023, and 20 in 2024. More than 66% of the articles were published in the last 3 years. In recent years, there has been significant academic interest in the field of PLs. Subfigure (b) illustrates the geographic distribution of selected studies. Europe and East Asia (particularly China and South Korea) represent the most active research regions in PL development, while emerging markets in South America and Africa remain underrepresented.

To further understand the intellectual structure of the PL research community, a co-citation network was constructed based on author-level references using *ResearchRabbit*. Subfigure (c) visualizes the citation relationships among the most influential authors in the field. The node size reflects the number of citations, while the edge thickness indicates the strength of cocitation between two authors. As shown in the network, several key contributors, such as Deutsch and Golany (2018); Lin et al. (2020); Sawik et al. (2022) and Orenstein et al. (2019) emerge as central nodes, reflecting their significant influence in shaping PL research, particularly in optimization modeling and last mile logistics applications. The clusters formed around these authors indicate thematic cohesion in specific topics, such as cost-minimization routing, mobile PL deployment, and integration with smart urban logistics. Recent contributors (e.g., Di Gangi et al., 2023; Ranjbari et al., 2023a; Zang et al., 2023) reflect a growing interest and diversification of research topics in the field. The citation network further illustrates the intellectual connections and evolving citation patterns within the literature on PLs.

This review categorized the studies by clustering similar methods and distinguishing them from others. As illustrated in subfigure (d), modeling is the most prevalent research method in PL studies, used in 52 articles. This highlights the importance of mathematical frameworks for understanding the dynamics of PL systems and forecasting future changes. The widespread adoption of the modeling approach suggests that constructing theoretical models for complex systems is crucial for guiding decision-making and optimization strategies. For example, Sawik (2024) integrated operational modeling with a multi-criteria decision-making framework based on the Analytic Hierarchy Process (AHP) to evaluate various delivery methods (e.g., private logistics, crowdsourcing) and determine the optimal combination in terms of cost, quality, flexibility, and sustainability.

The simulation methodology, used in six papers, is important for testing and assessing the operational efficiency of PLs. It enables researchers to replicate the workflow of PLs in a controlled virtual setting, thus mitigating real-world risks and costs. Consequently, simulation has become an essential tool for evaluating the functionality of PL operations. Moreover, the combination of modeling and simulation methods is used to investigate complex

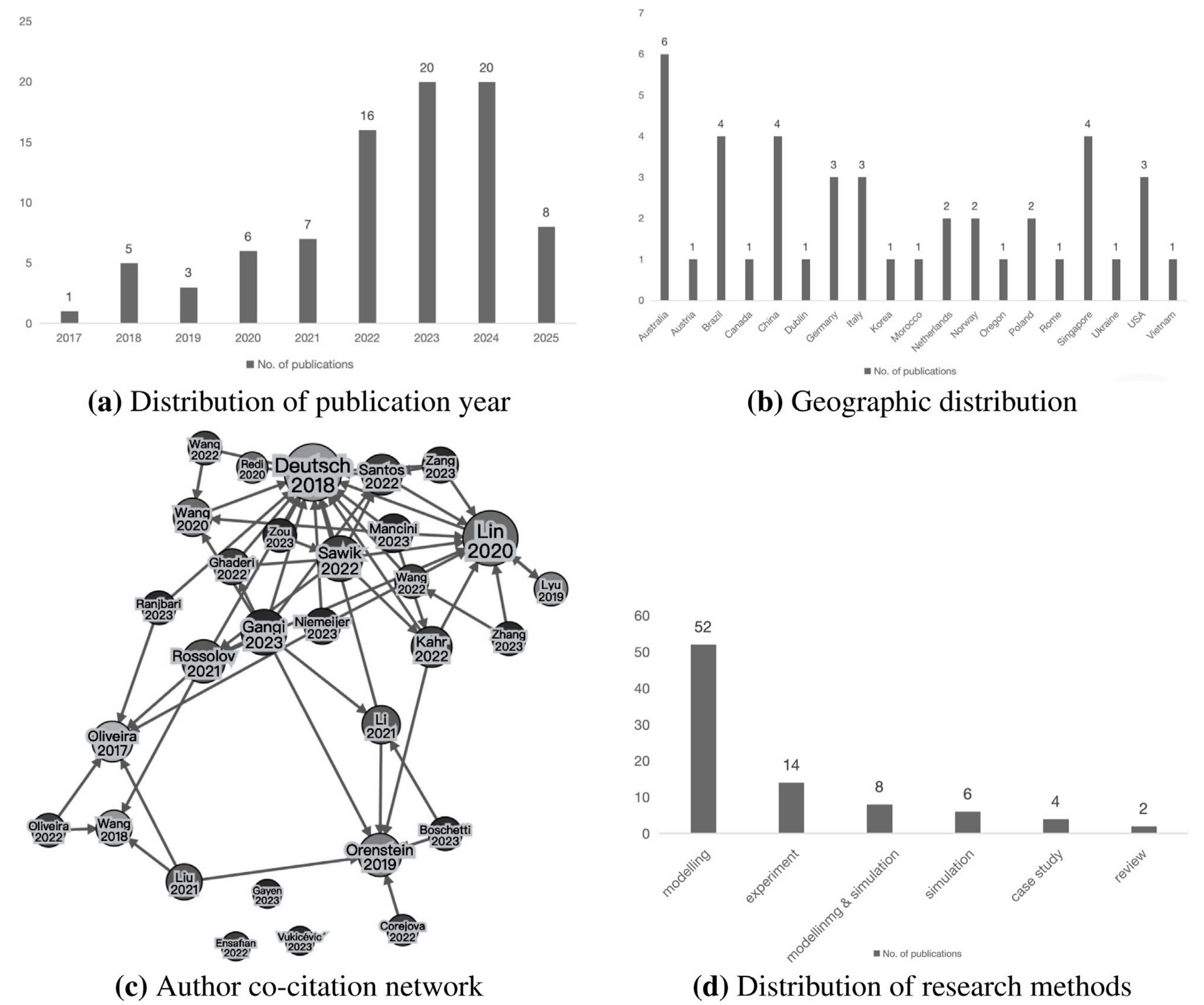

FIGURE 1
Overview of literature characteristics. **(a)** Distribution of publication year **(b)** Geographic distribution **(c)** Author co-citation network **(d)** Distribution of research methods.

real-world cases in eight papers. By integrating optimization or mathematical programming with simulation, researchers can offer insights that simplify the comprehension of complex systems' evolution over time or under varying conditions. In addition, it enables dynamic analysis that single methods may not provide. Through this type of research, managers can also make decisions that are not only theoretically but also validated through simulation. For example, managers can ensure a robust strategy for resource planning and budgeting. This combined method highlights the value of hybrid research approaches in providing a deeper understanding of the PL ecosystem. Similarly, the experiment methodology is used in the literature and cited in 13 papers. For example, Ranjbari et al. (2023a) combined a pre-test–post-test control group experiment with a difference-in-differences approach to analyze the causal effects of vehicle delivery and waiting times. The results confirm the environmental and efficiency benefits of parcel locker technology. Wang et al. (2018) and Ngan et al. (2025) used structural equation modeling (SEM) to analyze factors affecting customer intention. Furthermore, the multinomial logit model is also used as an experimental tool to explore PL demand (de Oliveira et al., 2017), carbon emissions (Niemeijer and Buijs, 2023), and profit (Kundu et al., 2025). Recently, Leung et al. (2023) integrated regression method with geospatial analysis to explore the spatial and temporal growth of PLs, providing insights into how urban form, population density, and accessibility factors influence the distribution and expansion patterns of PL networks over time.

The case study approach has also been employed in four articles, without being combined with other research methods. These studies offer real-life examples for PL systems to examine various aspects ranging from market management (Hoang et al., 2019) to customer value (Vakulenko et al., 2018), spatial distribution (Liu et al., 2021), and PL coverage (Lyu and Teo, 2022). We also note that two review papers have addressed the topic of PLs, although their focus differs from the present study. Mohri et al. (2024a) explored adoption and effectiveness of alternative delivery points (ADPs). Their analysis focused on how the success of ADPs depends on interdependencies between geographic location, consumer behavior, retailer integration, and infrastructural support. In another study, Janinhoff et al. (2024a) systematized and evaluated academic research on out-of-home delivery (OOHD) in last mile logistics. OOHD refers to any delivery method where parcels are delivered to a location outside the consumer's home, such as parcel lockers or parcel shops. They found that OOHD can improve delivery success rates, reduce costs, and emissions, particularly in dense urban areas. However, its adoption is highly context-dependent, influenced by factors such as consumer preferences, accessibility, and network design.

3.2 Distribution of study focus areas

Studies explore the operation of PLs from various perspectives, including company, consumer, city, country, and environment. Meanwhile, some studies combine multiple perspectives. From the companies' perspective, most studies focus on optimizing cost and delivery efficiency. PLs are introduced to complement or replace traditional last mile delivery methods. They help reduce delivery time, failure rates, and costs, while also improving the overall profitability of the delivery process. Companies also pay close attention to the design of the PL, including the optimal size and configuration of the PL (Ranjbari et al., 2023b), the long-term viability design of the PL compartment structure (Kahr, 2022), and the optimal capacity of the PL (Raviv, 2023). In addition, several studies discuss the PL network and coverage, including the optimal selection of PL locations and the construction of a modular PL network (see, e.g., Zou et al., 2024; Gayen et al., 2023).

Several research studies examine flexibility and convenience from the consumer's perspective. These investigations focus on improving consumer satisfaction with the delivery process and increasing the frequency of PL usage considering various factors, including consumer demands (Rossolov, 2023; de Oliveira et al., 2017), the selection of different delivery methods (El Moussaoui et al., 2022; Iannaccone et al., 2021), the preferred distance for PL usage, acceptance levels (Wang et al., 2018), and the social impact of PL (Pinchasik et al., 2023). These consumer-based studies employed surveys, data modeling, and other analytical methods to enhance consumers' satisfaction with the delivery process and the frequency of PL usage. In addition, Vakulenko et al. (2018) investigated the value created for consumers to better understand the customer experience and the perceived pros and cons of using PLs for collecting and returning parcels. In their study, Kundu et al. (2025) employed a value-based choice framework to identify the trade-offs that consumers make among economic, functional, emotional, epistemic, and social values. Their analysis revealed that consumers prefer home delivery due to its reliability and cost advantages.

Only a few studies have addressed the impact of PLs at the city or national scale, examining their effects on entire countries or regions. For example, Corejova et al. (2022) focused on the development of the APL network and the establishment of pick-up and drop-off points in Europe and the V4 countries[1]. They identified countries with sufficiently developed networks by comparing their development in terms of population and region. They also explored the relationship between the network and customer satisfaction with the delivery process. In another study, Hoang et al. (2019) analyzed management practices in the traditional retail market in the UK. They also identified the challenges to practice and assessed the impact of different management structures on operational success, using PL services as an example. Their research offers valuable insights for policymakers, operators, and researchers focused on local management and economic development. The study highlights that PL systems represent a crucial delivery solution for urban logistics.

Leung et al. (2023) evaluated the spatial and temporal growth of the Australia Post Express delivery locker system in Queensland. They assessed the frequency of locker usage, identified patterns in user collection times, and examined factors influencing PL usage. In a recent study, Ma et al. (2024) evaluated how spatial characteristics affect the performance of PL networks through spatial analysis. They found that high-density, mixed-use, and transit-proximate areas yield the best PL performance. In addition, Seghezzi et al. (2022) guided logistics and e-commerce stakeholders to optimize last mile delivery operations by evaluating the cost effectiveness of using PL in different geographical settings. They compared the cost of home delivery with the PLs. Later, Wang et al. (2024) investigated the strategic implications of Collection and Delivery Point (CDP) network sharing among competing LSPs. Using a game-theoretical model and numerical analysis, the authors assess whether and under what conditions it is beneficial for LSPs to share CDP infrastructure collaboratively.

Some studies combine different perspectives by looking at both companies and consumers. For example, they examine the delivery process from the provider's point of view while also considering the convenience of the end users (Grabenschweiger et al., 2021). These works often focus on factors such as delivery distance (Oliveira et al., 2022; Liu et al., 2023; Schwerdfeger and Boysen, 2022; Hong et al., 2019) and types of services offered (Kötschau et al., 2023). They also explore challenges such as the location of PLs under uncertain consumer demand (Mancini et al., 2023; Rabe et al., 2021) and evaluate operating costs on the company's side alongside the experience of the consumer (Wang M. et al., 2022; Ranjbari et al., 2023a). Furthermore, some research considers the relationship between companies and the environment, going beyond cost-effectiveness to assess sustainability factors such as emissions and traffic congestion (Sawik et al., 2022).

3.3 Analysis on operational problem types

This subsection focuses on the operational problems of PLs. As categorized in Figure 2, there are 66 articles focused on operational problems within the 86 related literature.

Forty-eight articles focus on APLs. Among them, the location problem is the main research direction (thirty-four papers). Instead of focusing on the location problem (twenty-four papers), researchers have also combined location problems with other operational problems (10 papers). They include location with layout problems (Kahr, 2022), capacity problems (Raviv, 2023), and pricing problems (Zhang W. et al., 2023). From the customer

1 The V4 countries refer to the Visegrád Group: the Czech Republic, Hungary, Poland, and Slovakia.

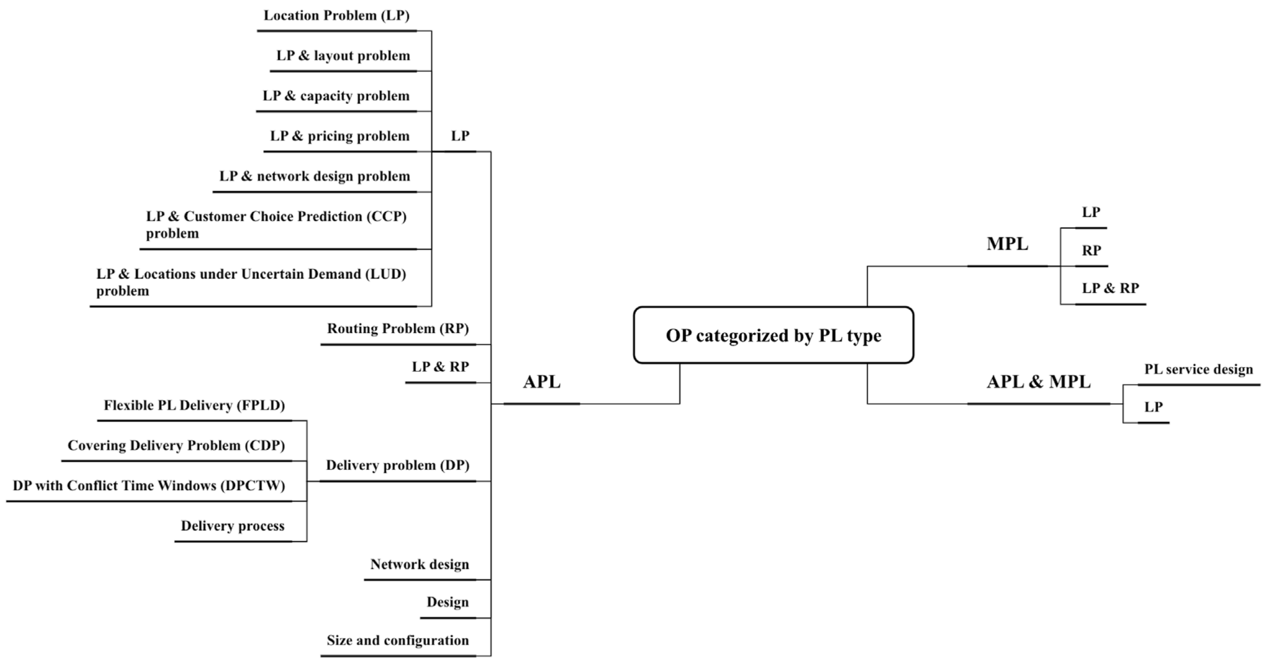

FIGURE 2
Operational problems (OPs) categorized by PL types.

perspective, researchers have combined customer choice prediction problems (Lin et al., 2020) and uncertain demand problems with APL location problems (Mancini et al., 2023). In addition, extensive research on location and network design is also conducted (Oliveira et al., 2022; Sawik et al., 2022). Fifteen papers have studied the related routing problems for APLs. Wang M. et al. (2022)'s research studied both the location problem and the routing problem of APLs. In addition, several studies examine various aspects of APL delivery, including flexible PL delivery (Orenstein et al., 2019), coverage-based delivery strategies (Vukićević et al., 2023), deliveries involving conflicting time windows (Zang et al., 2023), and the overall delivery process (Di Gangi et al., 2023). Zou et al. (2024) focused on the network design of PLs, while Faugère and Montreuil (2020) investigated the design of APL systems. Ranjbari et al. (2023b) further explored the optimal sizing and configuration of APLs.

The research on MPLs is less extensive than that on APLs. Researchers mainly focus on MPL location (Schwerdfeger and Boysen, 2020; Wang et al., 2020), and routing problems (Ensafian et al., 2023). Li et al. (2021) and Liu et al. (2023) studied MPL location and routing problems simultaneously. Some studies also integrate both types of PL, addressing challenges such as PL service design (Schwerdfeger and Boysen, 2022) and facility location (Kötschau et al., 2023).

4 Findings from thematic analysis for operational problems

This section analyzed the research methods involved in answering RQ1. We conducted a detailed thematic analysis of three research methodologies related to PL operational problems: modeling, simulation, and simulation-optimization.

4.1 Modeling studies in PL research

Table 1 provides a detailed overview of the problems addressed and the solution approaches adopted in the literature. This part focuses on modeling-based studies, summarizing key aspects such as research objectives, data characteristics, problem types, modeling approaches, and solution methods.

As presented in Table 1, 31 modeling studies focus on optimizing PL operations, addressing objectives ranging from cost reduction to improvement of revenue and efficiency. The complexity of modeling approaches can be categorized into stochastic methods (fourteen papers) and deterministic methods (thirty-eight papers). This distribution suggests that researchers primarily focus on deterministic system factors when addressing problems such as route optimization and location selection. In contrast, stochastic elements, reflecting uncertainty and randomness, receive comparatively less attention. Most existing research focuses on modeling static processes, implying that models are developed under fixed and predetermined environmental conditions. Although this approach is practical for addressing standardized problems, the operational environment of PL systems is inherently complex and dynamic, influenced by numerous unpredictable factors. Consequently, static models may struggle to fully capture and represent these real-world fluctuations in practice.

Common operational challenges addressed in the literature include routing (15 papers), location (19 papers), capacity (one paper), and coverage (one paper). In addition, several studies focus

TABLE 1 Summary of modeling-focused publications.

References	Objective	Data	Operational problem	Modeling approach	Solution approach
Hong et al. (2019)	Distance	D	RP	TSPTW	Two-phase algorithm
Orenstein et al. (2019)	Cost, Penalties	S	FPLD	MILP	Petal heuristic, saving heuristic, Tabu search
Enthoven et al. (2020)	Cost	D	RP	MIP	ALNS
Faugère and Montreuil (2020)	Efficiency, Asset utilization, Customer satisfaction	S	Design	LBDP-FC, LBDP-MT	OA
Lin et al. (2020)	Locations	D	LP, CCP	MNL, MILP	QT-LA
Schwerdfeger and Boysen (2020)	Fleet size	D	LP	MIP	GH
Wang et al. (2020)	Cost	S	LP	RO, ILP	CP, BB
Grabenschweiger et al. (2021)	Cost	D	RP	VRPHLB	MHSM, ALNS, IFFD
Iannaccone et al. (2021)	Customer choice	D	–	DCM, MDF	MWTP estimation
Li et al. (2021)	Cost	D	LP, RP	MIP	HCWH, EHCWH
Schaefer and Figliozzi (2021)	Location strategy	D	–	Geographical tools, cluster analysis	KDE, hierarchical and K-means clustering
Yu et al. (2021)	Cost	D	RP	TSP	DSPS
Che et al. (2022)	Coverage, Overlap, Idle capacity	D	LP	MOOM	TA-NSGA-II approach
Dos Santos et al. (2022)	Cost, Distance	D	RP	MILP	OA
El Moussaoui et al. (2022)	Customer choice	D	–	ML algorithms	Decision tree, random forest, Naive Bayes, KNN, OA
Ghaderi et al. (2022)	Delivery success rates, Detours	D	LP	Novel model	Two-phase algorithm
Kahr (2022)	Economic performance, Long-term viability	S	LP, layout	ILP	Benders decomposition
Lin et al. (2022)	Profit	S	LP	TLM, BNL, MNL	MICQP
Peppel and Spinler (2022)	Cost, Emissions	D	LP	MNL, MILP	–
Schwerdfeger and Boysen (2022)	Cost	S	PLSD	MIP	MSH, TS
Seghezzi et al. (2022)	Compare solutions	D	–	Analytical cost models	–
Wang et al. (2022a)	Cost	D	LP, RP	MIP	BP
Wang et al. (2022b)	Cost, Distance	S	LP	RO	LP
Boschetti and Novellani (2023)	Cost, Time	D	RP	TSP	BC
Dell'Amico et al. (2023)	Distance	D	RP	MILP	BC
Di Gangi et al. (2023)	Time	D	DP	CC	GA
Ensafian et al. (2023)	Cost	D	RP	MILP	ABSM
Gayen et al. (2023)	Location	S	LP	DHq-ROFS	AO based on AA
Mancini et al. (2023)	Customers number	S	LP, LUD	SPM	OA
Pinchasik et al. (2023)	Cost, Traffic, Emissions, Societal cost	S	RP	DDM	OA
Raviv (2023)	Cost	S	LP, capacity	MILP	DTMC, PWLA
Rossolov (2023)	Demand	D	–	RUM, DCM, BNL	–

(Continued on following page)

TABLE 1 (*Continued*) Summary of modeling-focused publications.

References	Objective	Data	Operational problem	Modeling approach	Solution approach
Vukićević et al. (2023)	Time	D	CDP	MILP	VNS
Yang et al. (2023)	Profit	S	LP	BP	GA
Zang et al. (2023)	Cost	D	DPCTW	MILP	GH, BC, VNS
Zhang et al. (2023)	Profit	S	LP, pricing	CO	MPCC
Zhang et al. (2023a)	Cost	D	LAP	MILP	–
Stokkink et al. (2024)	Profit	D	RP, pricing	IP	Column-and-Row Generation Algorithm
Zhu et al. (2024b)	Time	D	RP	MILP	VNS
Janinhoff et al. (2024b)	Cost	D	MT-VRPDO	MILP	ALNS
Wyrowski et al. (2024)	Profit	D	RP	MILP	Gurobi
Wang et al. (2024)	Cost	S	RP, recourse strategies	Two-stage Stochastic Programming	SAA
Li et al. (2024)	Strategic collaboration between LSPs	D	Game-theoretical model	Nash Equilibrium	–
Peppel et al. (2024)	Cost	D	RP	MILP	Greedy heuristic
Zhu et al. (2024a)	Distance	D	LDDP	2-stage MIP	BC
Zou et al. (2024)	Cost	D	LP, resource allocation	2-stage resource problem	GRASP
Ozyavas et al. (2025)	Cost	D	LP, RP	Multi-objective MILP	BP
Kötschau et al. (2025)	Cost	D	MHDPL	MILP	ILS
Korkmaz et al. (2025)	Cost	D	LP, RP	ILP	ILP-based decomposition heuristic
Mohri et al. (2025)	Cost	D	PBC, OD	MIP	Lagrangian Relaxation
Yu and Anh (2025)	Cost	D	RP	EVRP-TW-PR-CL	LNS
Rose et al. (2025)	Customer adoption	D	Regression	ANOVA	–

D, deterministic; S, stochastic; HC, hierarchical cluster analysis; RP, routing problem; TSPTW, traveling salesman problem with time window; FPLD, Flexible PL, delivery; ALNS, adaptive large neighborhood search; LBDP-FC, Fixed-Configuration Locker Bank Design Problem; LBDP-MT, modular tower based locker bank design problem; OA, optimization algorithm; CCP, constrained combinatorial problem; QT-LA, quadratic transform with linear alternating algorithm; GH, greedy heuristic; RO, robust optimization; CP, cutting plane method; BB, Branch-and-Bound; VRPHLB, VRP, with Heterogeneous Locker Boxes; MHSM, MetaHeuristic Solution Method; IFFD, Iterative First-Fit Decreasing; DCM, discrete choice modeling; MDF, market demand forecasting; MWTP, marginal willingness to pay; HCWH, hybrid clarke and wright heuristic; EHCWH, enhanced hybrid clarke and wright heuristic; KDE, kernel density estimation; DSPS, Dijkstra's Shortest Path Search; MOOM, MultiObjective Optimization Model; TA-NSGA-II, TAguchi method and Non-dominant Sorting Genetic Algorithm II; TLM, threshold luce model; BNL, Bi-Nomial Logit model; MICQP, Mixed-Integer Conic Quadratic Program; PLSD, PL, service design; MSH, Multi-Stage Heuristic; TS, tabu search; BP, bilevel programming; BC, Branch-and-Cut; DP, delivery process; CC, constrained combinatorial problem; GA, genetic algorithm; ABSM, Adaptive Backtracking-Simulated annealing Metaheuristic; DHq-ROFS, Dual Hesitant q-Rung Orthopair Fuzzy Set; AO, based on AA, Aggregation Operators based on Aczel-Alsina triangular norms; LUD, locations under uncertain demand; SPM, stochastic programming model; DDM, Data-Driven Modeling approach; DTMC, Discrete-Time Markov Chain; PWLA, PieceWise Linear Approximation; RUM, random utility modeling; CDP, collection and delivery points; VNS, variable neighborhood search; DPCTW, delivery problem with conflict time windows; CO, convex optimization; MPCC, mathematical program with complementarity constraints; ND:TableNotes Network Design; SAA, sample average approximation; LAP, location assignment problem; PBC and OD, probabilistic behavioral choice models with an operational design problem; GRASP, greedy randomized adaptive search procedure; LDDP, Locker-Based Drone Delivery Problem; MHDPL, mobile home delivery parcel locker problem; ILS, iterated local search; MT-VRPDO, VRP, with Delivery Options and Multiple Trips; EVRP-TW-PR-CL, electric vehicle routing problem with time windows, Partial Recharges, and Covering Locations; LNS, large neighborhood search.

on designing and expanding the coverage of PL networks. Faugère and Montreuil (2020) explored the PL design to improve its efficiency and utilization. The adopted modeling methods, such as random utility models, discrete choice models, SEMs, and MNL, help to describe and predict the behavior of the system accurately. The modeling methods for most operational problems are MILP, MIP, and ILP. Some studies extend the basic TSP by adding time windows to the model, making the model closer to realistic situations (Hong et al., 2019). In El Moussaoui et al. (2022)'s study, they applied related machine learning models to analyze customer choices. As an exact algorithm, branch-and-cut (Dell'Amico et al., 2023; Boschetti and Novellani, 2023) and branch-and-price (Wang M. et al., 2022) algorithms are mainly used. Various approximation algorithms are also proposed, including heuristics, metaheuristics, and machine learning algorithms.

4.2 Simulation studies in PL research

Table 2 presents several simulation studies on PL systems that employ multiple modeling approaches to address various problems. Simulation studies can test and optimize policies without actually

TABLE 2 Summary of simulation-focused publications.

References	Objective	Data	Operational problem	Modeling approach	Solution approach
Rabe et al. (2021)	Cost, Demand	S	LP	SDSM, CFLP	MCS
Liu et al. (2023)	Fleet size, Distance, Service delay	S	LP, RP	MILP, HQM	K-means clustering, Global and local search, dynamic route adjustments
Ranjbari et al. (2023b)	Environmental and logistical challenges	S	SC	DES-QTC	Simulation of various configurations, PMA, OC
Mohri et al. (2024b)	Beneficiaries, social and behavioral implications	D	—	PS	QA, CA, Stakeholder analysis
Gutenschwager et al. (2024)	Carbon emissions	D	—	Discrete Event Simulation	Benchmarking
Rosca et al. (2024)	Operational efficiency	D	—	ABS, MCS	

SDSM, system dynamics simulation model; CFLP, Multi-period capacitated Facility Location Problem; MCS, monte carlo simulation; HQM, Hybrid Q-learning-network-based Method; SC, size and configuration problem; DES-QTC, discrete event simulation with queuing theory concept; PMA, performance metrics analysis; OC, optimization criteria; PS, probabilistic simulation algorithm; QA, quantitative analysis; CA, comparative analysis; ABS, Agent-Based Simulation.

running the system by simulating complex operating environments. This approach is a highly flexible, cost-effective, and powerful tool for understanding and improving systems. Three articles focused on APL, while one publication explored the application of MPL. Simulation research mainly focuses on dynamic systems (three papers) and is primarily developed for operational problems.

For optimization problems, various types of methods are used, including SDSM combined with multi-period CFLP (Rabe et al., 2021), DES-QTC (Ranjbari et al., 2023b), MILP, and HQM (Liu et al., 2023). In another study, Liu et al. (2023) applied K-means clustering, global and local search methods, and dynamic route adjustment procedure. In their study, Mohri et al. (2024b) used three types of analysis to discover the social and behavioral implications of beneficiaries. This includes QA, CA, and stakeholder analysis. To investigate the environmental impact of APLs and HD, Gutenschwager et al. (2024) developed a discrete-event simulation to model delivery routes and calculate CO_2 emissions based on vehicle types, delivery frequencies, and customer retrieval patterns. To analyze whether different factors affect the performance of the APLs, Rosca et al. (2024) evaluated the performance of the APLs through a novel hybrid approach combining Agent-Based Simulation and Monte Carlo simulation. The authors developed a simulation model that represents agents, including couriers, lockers, and customers, utilizing randomization to reflect real-world variability. They found that APLs significantly reduce delivery times, operational costs, and failure rates, particularly in densely populated urban areas. APLs also perform best when demand is high and the density of the locker is sufficient.

4.3 Simulation-optimization studies in PL research

Table 3 presents simulation–optimization studies to highlight how proposed methods are applied to address the operational challenges of different PL types.

The simulation-optimization method can be applied in practical research to deal with complex problems in the PL system. These methods enable researchers to evaluate potential improvements by simulating and analyzing various operational scenarios and strategies. For example, using optimization models and sophisticated simulation algorithms, researchers test different configurations and operation strategies to discover the most cost-effective or optimal solutions to service efficiency, (Redi et al., 2020; Yu et al., 2022). Simulation optimization can also be used to investigate different strategies. For example, to investigate how collaboration can be established between operators with locker resources and those without, Pang et al. (2024) developed a single-period stochastic profit maximization model. The model explicitly defines the profit functions and optimal decision variables for two types of LSPs: asset-based and non-asset-based LSPs. By incorporating four different cost structure scenarios into the mathematical model and performing simulations, the study compares the feasibility of cooperation under varying cost conditions. The findings suggest that PL sharing can improve both logistics efficiency and profitability.

5 A thematic exploration of sustainability aspects in PL systems

To answer RQ2, this section aims to synthesize the literature related to sustainability and the current academic perspective on the impacts of PL on sustainability. Sustainability is a complex and multidimensional concept that has been extensively debated in academic literature. Brundtland (1987) defines sustainable development as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. We frame sustainability through three interrelated dimensions, based on the widely accepted "triple-pillar" model (Purvis et al., 2019). Table 4 summarizes the published works from environmental, economic, and social perspectives.

Following the coding and thematic analysis of the reviewed literature, this study identifies that APL research primarily focuses on aspects of economic sustainability, particularly cost–benefit analysis (30 articles) and operational efficiency (14 articles). In terms of environmental sustainability, seven studies address the

TABLE 3 Summary of simulation-optimization focused publications.

References	Objective	Data	Operational problem	Modeling approach	Solution approach
Deutsch and Golany (2018)	Profit	S	LP	0–1 ILP	Three-phase algorithm
Redi et al. (2020)	Cost	D	LP	ILP	SA, HO
Oliveira et al. (2022)	Distance	D	LP, Network	P-median problem	Scenario-based simulations
Sawik et al. (2022)	Profit, Cost, Delivery failure	D	LP, Network	Mathematical programming	AnyLogic Software, CPLEX Solver
Yu et al. (2022)	Cost	D	LP	VRPSPDPL	SA
Alves et al. (2023)	Cost	S	—	ABM	Simulation techniques
Kötschau et al. (2023)	Efficiency, Customer service	D	LP	MIP, HLLP	Simulation for validation
Pang et al. (2024)	Profit	S	SPSP	SPSP using normally distributed demand	Scenario-based simulations

SA: simulated annealing; HO: heuristic optimization; ABM: Agent-Based Modeling; HLLP: heterogeneous locker location problem; SPSP: Single-Period Stochastic Profit modeling.

reduction of GHG emissions, while 25 focus on environmentally related operational practices. Social sustainability studies on APLs are primarily centered around customer choice and demand (22 articles), accessibility and convenience (7 articles), user adoption and satisfaction (11 articles), and the development of locker networks (17 articles). In contrast, research on MPL remains relatively limited. However, existing studies exhibit trends similar to those observed in APL research. Specifically, seven articles explore MPL cost–benefit dynamics, and four investigate operational efficiency. The social sustainability dimension of MPLs is less explored, with only a few studies addressing customer choice and demand (4 articles), accessibility and convenience (2 articles), and impacts on regional transportation (3 articles).

5.1 Economic sustainability

Sustainability has become a must for all economies worldwide (Seuring and Müller, 2008). Economic sustainability refers to the ability of PL systems to generate long-term financial viability without compromising social or environmental welfare. It includes considerations such as lifecycle cost analysis, resilience to demand fluctuations, and equitable access on different scales of businesses (Jeronen, 2023). From an economic sustainability perspective, most studies focus on the logistics company's point of view, although some research also examines it from the perspective of various beneficiaries.

5.1.1 Cost-benefit analysis

Researchers have studied the economic sustainability of PL based on cost-profit analysis, focusing on cost optimization and improvement of profitability. These studies aim to reduce operational and delivery costs while improving overall economic benefits through strategic deployment and technological innovation. Recent research has focused on optimizing PL costs using various models and strategies. Wang Y. et al. (2022) used robust optimization models to meet uncertain demand while minimizing operating costs. Rabe et al. (2021) optimized APL systems to determine optimal locations and balance service quality with operating costs. A number of studies, including Dell'Amico et al. (2023), Enthoven et al. (2020), Redi et al. (2020), and Yu et al. (2022), focused on minimizing transportation and delivery costs by developing models and strategies for optimal routing and placement, addressing problems such as pick-up and delivery with time windows, two-echelon VRP with locker facilities, and VRPSPDPL.

Several studies have proposed optimization methods to improve urban parcel delivery systems, each with distinct modeling approaches and problem settings. For example, Ranjbari et al. (2023b) employed a discrete event simulation combined with the queueing theory concept (DES-QTC) to configure PLs in residential buildings, focusing on optimizing the size and configuration of the PL. Wang M. et al. (2022) introduced a MIP model to determine pickup station locations while jointly minimizing station opening, routing, and delivery vehicle costs. Zang et al. (2023) proposed an exact branch-and-price method to coordinate PL delivery with service time windows in dense urban areas. Boschetti and Novellani (2023) developed a TSP-based optimization model that integrates UAVs and lockers to reduce the total delivery and pickup time. In another study, Grabenschweiger et al. (2021) introduced the VRP with heterogeneous locker boxes (VRPHLB) constraints, minimizing routing and compensation costs under contractual limitations. These studies collectively demonstrate that different modeling techniques from heuristic to exact approaches can address specific aspects of PL optimization, including location, routing, temporal constraints, and hybrid fleet configurations. Mohri et al. (2025) placed the PLs in a public transport station through which small and lightweight packages are assigned to passengers to carry out the delivery. In another study, Peppel et al. (2024) designed a Multinomial Logit Model and estimated the route costs. Their research demonstrated that MPL integration leads to additional cost savings of 8.7%. In Korkmaz et al. (2025) research, they used MPLs that are placed by electric vehicles. They found that the total cost is

TABLE 4 Overview of publications focusing on sustainability.

PL type	Dimension	Perspective	Description	No. of articles
APL	Economic	Stakeholder	Asset utilization	3
			Beneficiaries	3
		PL company	Cost-benefit analysis	30
			Delay	
			Labor utilization (courier)	—
			Operational efficiency	14
			Time management	4
	Environmental	Emissions Operational practice	GHG reduction	10
			—	25
	Social	Customer	Accessibility and convenience	7
			Access time	1
			Adoption and satisfaction	11
			Choice and demand	22
			Equity in access	1
			Travel distance (to collect/drop parcels)	3
			Safety and security	1
			Service provided (additional service)	1
			Societal damage costs	1
			Penalties (for long-time not picking up)	1
			Value	2
		Region	Network level	17
			Rural planning	1
			Traffic	4
			Urban planning	3
MPL	Economic	Stakeholder	Asset utilization	—
			Beneficiaries	—
		PL company	Cost-benefit analysis	7
			Delay	1
			Labor utilization (courier)	1
			Operational efficiency	4
			Time management	—
	Environmental	Emissions Operational practice	GHG reduction	2
			—	2
	Social	Customer	Accessibility and convenience	2
			Access time	1
			Adoption and satisfaction	—
			Choice and demand	4
			Equity in access	—

(Continued on following page)

TABLE 4 (*Continued*) Overview of publications focusing on sustainability.

PL type	Dimension	Perspective	Description	No. of articles
			Travel distance (to collect/drop parcels)	1
			Safety and security	—
			Service provided (additional service)	—
			Societal damage costs	—
			Penalties (for long-time not picking up)	—
			Value	—
		Region	Network level	—
			Rural planning	—
			Traffic	3
			Urban planning	—

Note: "—" indicates that no relevant studies were identified for this category during the review period.

reduced by up to 4.52% for companies in the trilateral collaboration scenario with a single warehouse and by up to 7.32% in the trilateral collaboration scenario with multiple warehouses. A number of studies optimized PL costs by building optimal locker networks. For example, Deutsch and Golany (2018) improved the delivery efficiency and cost effectiveness by determining the optimal number, location and package size of PLs. Peppel and Spinler (2022) developed a methodology for the design of the APL network, achieving cost savings of up to 11%.

Although less general, some research on profit optimization specifically targets PLs. Yang et al. (2023) explored how investment budgets affect expected profits, building a two-layer programming model to optimize the location of smart community PLs to maximize the profit of third-party suppliers. Sawik et al. (2022) optimized APL facility locations to maximize profits and minimize costs. Studies comparing home delivery and PL provide valuable information for stakeholders considering the transition or integration of these systems. Seghezzi et al. (2022) found out that PL offers lower delivery costs and investment requirements compared to home delivery, regardless of the implementation area. Zhang W. et al. (2023) reduced last mile delivery costs by encouraging customers to choose self-service instead of home delivery, thereby improving profitability and service efficiency. In general, PLs offer numerous opportunities to optimize economic sustainability, ranging from cost control to enhanced profitability, thereby promoting greater efficiency within the logistics industry.

5.1.2 Operational efficiency

The operational efficiency of PLs is related to direct costs and benefits, as well as improving the long-term sustainability and competitiveness of the logistics system through technology and innovative services. In evaluating usage patterns and operational efficiency studies, researchers analyze different aspects of PLs. For example, Leung et al. (2023) analyzed trends and seasonal variations in PL use. They observed peak usage during holidays and peak hours during weekdays, highlighting the impact of consumer behavior on PL use. Consumer preferences are another primary academic interest. El Moussaoui et al. (2022) identifies factors influencing consumer choice of CDPs. They provided insights to optimize delivery services based on consumer behavior. Lin et al. (2020) integrated customer choice into the design of the locker network to improve delivery efficiency. Dynamic positioning strategies also contribute to enhancing PL efficiency. Schwerdfeger and Boysen (2020)'s study optimized the MPL by adjusting the positions, allowing flexible placement to improve service coverage. In addition, technological integration has improved the operational efficiency of PL.

Researchers have advanced urban logistics efficiency through various approaches, including facility location, route planning, customer preferences, innovative delivery solutions, network design, multimodal collaboration, and performance evaluation. Studies on delivery preference and PL routing have also contributed to improving urban logistics systems. Enthoven et al. (2020) integrated customer preferences into their model to improve logistics efficiency. Zang et al. (2023) focused on minimizing delivery and pick-up costs while adhering to time constraints, improving systems' efficiency and effectiveness. Innovative and combined delivery methods, such as crowdsourced or MPLs with PLs, have also been explored. Ghaderi et al. (2022) and Stokkink et al. (2024) optimized crowdsourced delivery, while Kötschau et al. (2023) analyzed MPL deployment. Kötschau et al. (2023) and Liu et al. (2023) improved service flexibility and efficiency in delivery systems, with the former arguing for the benefits they offer, and the latter identifying critical factors in MPL-based systems and implementing dynamic routing strategies. The researchers also analyzed operational efficiency from a network design perspective, such as optimal locker configuration (Faugère and Montreuil, 2020) and strategic insights (Grabenschweiger et al., 2021). In addition, Lyu and Teo (2022) examined the efficiency of the locker alliance network to determine the optimal density and coverage for Singapore. In Peppel et al. (2024) research, they combined home delivery, APLs, and MPLs to determine optimal delivery patterns that minimize total cost while meeting customer demands. Janinhoff et al. (2024b) pointed that flexible allocation of lockers and home delivery can improve the delivery success rate and route density, which can increase resource utilization and operational efficiency.

5.2 Environmental sustainability

Environmental sustainability denotes the capacity to maintain or improve environmental health, through efficient resource usage, emission control, and long-term ecological impact (Morelli, 2011).

5.2.1 Emissions reduction

PLs can reduce the driving distance and time required in the traditional delivery process, effectively reducing GHG emissions. Traditional delivery methods often necessitate multiple attempts to reach homes or offices, resulting in increased traffic congestion and higher emissions. Using PLs, deliveries can be centralized, and consumers can pick up their parcels. The innovative delivery process can reduce the round-trip and driving mileage of the delivery vehicles.

Niemeijer and Buijs (2023) examined the carbon impact of the pick-up points, finding that the potential for net positive effects of carbon emissions is most significant when the pick-up points are established in urban environments. Janinhoff et al. (2024b) stated that the use of PL can significantly reduce the carbon footprint of service providers. Pinchasik et al. (2023) estimated that CO_2 emissions could be reduced by 13%–32% by replacing home delivery with PLs. In another study, Peppel and Spinler (2022) developed a methodology for designing a PL network that minimizes emissions and costs during delivery and collection, with findings showing that PLs have a positive impact on reducing emissions in urban areas (up to 2.5%), but can generate additional emissions in less populated areas (4.6%). Based on a simulation-based comparison analysis, Gutenschwager et al. (2024) stated that PLs can reduce carbon emissions by about 60% in high-density urban areas. In another study, Ozyavas et al. (2025) used PL as both the collection and transfer points. Designing a multi-level distribution network reduces the distance of home deliveries while minimizing total delivery costs, thereby significantly reducing carbon emissions. Peppel et al. (2024) showed that integrating MPLs leads to extra CO_2e emissions savings of up to 5.4%.

5.2.2 Operational practices

Logistics companies can manage delivery and storage processes more efficiently by utilizing PLs, thereby improving operational efficiency and environmental sustainability. This is achieved by adjusting delivery plans based on actual demands, consolidating orders to reduce idle and half-load situations, and combining different delivery capabilities with lockers to enhance efficiency and flexibility. Several studies have investigated how enhancing PL operational practices can improve environmental sustainability. Janinhoff et al. (2024b) designed intelligent delivery networks to compare different delivery options, finding that integrating orders for PLs significantly reduced delivery costs. Ranjbari et al. (2023b) guided for determining the correct locker size and configuration, highlighting that the proper setup can reduce the workload of building managers and minimize environmental challenges in dense urban areas. Redi et al. (2020) included locker facilities in the routing problem to improve efficiency and reduce costs. Kahr (2022) proposed an optimization framework to design the structure of the PL compartment. Their results suggest that small and medium size compartments are more effective in meeting customer needs.

Combining EVs and PLs can address the challenge of the last mile carbon footprint. Vukićević et al. (2023) showed that the integration of EVs with PLs reduced delivery failures and increased the efficiency of energy use. Oliveira et al. (2022) explored integrating freight services with public transport infrastructure, reducing externalities of urban freight by placing PLs at public transport nodes. Enthoven et al. (2020) combined PLs and freight bikes to improve the sustainability of the urban delivery network, reducing traffic congestion and pollution. Wang M. et al. (2022) optimized locker locations and delivery plans for GVs, while Zang et al. (2023) explored optimal coordination between door-to-door and locker deliveries in conflicting time windows. Ghaderi et al. (2022) presented a novel crowdsourced LMD problem using PLs as exchange points, reducing trip detour times and improving delivery success rates by up to 5%. Stokkink et al. (2024) considered PLs as transfer stations for crowdsourcing delivery system, the overall service level and revenue increased by about 30%.

Innovative delivery methods involving lockers have also been explored. Zou et al. (2024) designed a lock-and-drone delivery system where trucks transport parcels to lockers and drones complete the final delivery. This innovative delivery system significantly improved delivery speed and cost efficiency. Li et al. (2021) developed a system in which couriers collaborate with MPL to expand depot coverage and reduce the number of depots needed. Di Gangi et al. (2023) linked transportation services to last mile delivery using PLs, demonstrating improved delivery on small islands through integration with naval services. Boschetti and Novellani (2023) analyzed a delivery routing system that combines drones, lockers, and traditional trucks, offering various delivery modes to customers. Yu et al. (2022) formulated VRP for simultaneous pickup and delivery with PLs, considering home and PL delivery modes. Dos Santos et al. (2022) integrated PLs with occasional couriers (OCs), showing that OC usage positively impacts transportation costs and distance traveled by the dedicated fleet, especially when using larger capacity lockers. In response to the locker-based drone delivery system, Zhu et al. (2024b) studied how to minimize task completion time (makespan) while meeting all customer needs.

5.3 Social sustainability

With rapid urbanization and the exponential rise of e-commerce, PLs have moved beyond simply optimizing traditional delivery models. They now function as an essential infrastructure to improve the efficiency of urban logistics and to support socially sustainable development. A central aspect of this role involves the promotion of social sustainability to ensure equitable access, inclusive service design, and the creation of public value through the deployment of PLs. Specifically, this involves ensuring user safety, operational convenience, and improved service availability, particularly for underserved or vulnerable populations (Purvis et al., 2019).

5.3.1 Adoption and satisfaction

Customer adoption and satisfaction with PLs are crucial to promoting social sustainability. These indicators directly influence the shopping experience and indirectly support environmental protection and community development. Yang et al. (2023) built a BP model to optimize the location of smart PLs in the community, showing that improving user satisfaction with PLs is both a market strategy for companies and a key part of profit strategies. Ranjbari et al. (2023a) used a pre-test and post-test control group experiment framework and a difference-in-difference analysis framework to analyze PL potential to improve convenience and social acceptance. They found that up to 96% residents were satisfied with the PLs. Hong et al. (2019) developed a routing algorithm for on-demand logistics services, enhancing the ability to solve optimization problems and ensuring high customer satisfaction through effective route optimization. Faugère and Montreuil (2020) developed an optimization model for PLs to maximize customer satisfaction, thus improving service efficiency and promoting environmentally friendly logistics practices. Hu et al. (2024) identified what motivates consumers to adopt smart food lockers during public health crises. They found that perception of health risk, social norms, and perceived usefulness are key drivers. Rose et al. (2025) investigated how the structure of the information and the characteristics of the consumers influence the adoption of PLs. The findings reveal that gain-framed messages are more effective than loss-framed ones, especially for consumers with high environmental concern and low risk aversion. Innovation also plays a moderating role. Several studies have employed SEM frameworks to assess user usefulness and convenience in the usage of PL [e.g., Jang et al. (2024), Ngan et al. (2025), Jang et al. (2024)] explored to understand what influences the intention of consumers to adopt APL systems under pandemic conditions. They found that consumers' intention is driven by ease of use, usefulness, security, and health-related factors. Through a survey in Vietnam; Ngan et al. (2025) extended the model of unified acceptance and technology use (UTAUT) to identify the factors that influence consumers' intention to use smart parcel lockers. Then, they used the covariance-based SEM (CB-SEM) framework to explain the psychological and behavioral factors that influence the intention of consumers to adopt PLs. They showed that performance expectancy, effort expectancy, social influence, innovation, and compatibility have a positive effect on users' intention, while perceived risk has a negative effect.

5.3.2 Accessibility and convenience

PLs offer customers flexible parcel collection options, allowing them to pick up parcels at their convenience, which is particularly beneficial for those with irregular schedules. By improving accessibility and convenience, PLs contribute positively to individual quality of life, community wellbeing, environmental protection, and economic development. Schaefer and Figliozzi (2021) studied Amazon locker locations in Portland, Oregon, finding that PLs tend to be located in mixed-use areas, improving accessibility for a large part of the population. El Moussaoui et al. (2022) analyzed CDPs' potential locations to improve convenience for e-consumers, providing logistics companies with insights for more personalized services. Vukićević et al. (2023) argued that PLs could significantly increase the comfort of the recipient by reducing failed delivery attempts. Oliveira et al. (2022) explored integrating lockers with public transport infrastructure to provide accessible and equitable services, particularly in small and medium-sized cities. Gayen et al. (2023) used a multi-criteria group decision-making method to select optimal PL locations, finding that post offices are ideal due to their centrality and accessibility.

5.3.3 Equity in access

Equity in access ensures that everyone, regardless of their economic status or residence, can easily use PL services. This is particularly important for residents in remote or resource-poor areas, as it helps improve overall social wellbeing. Schaefer and Figliozzi (2021) emphasized that the current location of Amazon PLs in the US could be improved to cover traditionally under-served populations, ensuring equitable access for all community members, especially in remote areas. Easy access to logistics services can significantly improve the quality of life, particularly in the delivery of essential health products, educational materials, and necessities. By ensuring equitable access, PLs help reduce social inequalities and promote inclusive growth.

5.3.4 Regional impact on city and rural planning

The application of PLs in urban and suburban planning plays a vital role in promoting social sustainability by enhancing urban transportation, optimizing land use, supporting regional economic development, promoting social inclusion, and fostering environmentally sustainable development. Lachapelle et al. (2018) explored PL development, site characteristics, and regional location characteristics in five South East Queensland cities and discussed the impact on the planning of urban and transportation dominated by cars. Their study highlighted the importance of documenting and evaluating PL locations to ensure optimal integration with urban and transport planning. Leung et al. (2023) conducted empirical research on the usage of PL in Australia, finding that usage patterns are closely related to the pace of life of urban residents. They presented novel empirical findings of the spatial and temporal use patterns of PLs, which contribute significantly to urban mobility and sustainability goals. Seghezzi et al. (2022) compared PL and home delivery in urban and rural areas. They pointed out that the benefits of PL were more significant in rural areas, providing reliable and economical logistics solutions that support social and economic development in populated regions.

5.4 Discussion

PLs not only provide consumers with convenience, but also have a significant impact on the urban economy, the environment, and social development. This highlights the key role of PL solutions in supporting the future of sustainable development. At the economic level, cost-profit analyzes reveal various strategies for optimizing operating costs and profitability. In terms of operational efficiency, research emphasizes the integration of technology and innovative services, which improve the overall effectiveness and responsiveness of logistics systems. Regarding environmental sustainability, PLs significantly reduce GHG emissions by minimizing travel distance and time, helping to protect the environment. By optimizing the delivery and storage process through technological integration and innovative operations, PLs reduce waste and improve resource use efficiency. As a green logistics practice, PLs offer companies an effective path to more environmentally friendly logistics operations. In terms of social sustainability, PLs improve the accessibility and convenience of delivery services, particularly by providing broad community coverage. These analyses of current academic research support the utility of PLs as an effective last mile delivery solution and highlight their potential to drive sustainability strategies.

6 Research gaps and future research

Combining the descriptive and thematic analysis, the existing literature was examined in detail and assessed from two key research perspectives: operational challenges and sustainability impacts. However, within the scope and search criteria adopted in this review, limited evidence was found regarding the third research question, which focuses on the application of AI technologies to PL solutions. Acknowledging these limitations, this section presents an exploratory discussion of the identified gaps, suggests plausible reasons for their occurrence, and outlines directions for future research. It is important to note that the literature reviewed in this study was limited to specific databases and search criteria (e.g., Scopus, Web of Science). As a result, the limited representation of certain topics may reflect methodological constraints rather than a definitive absence of existing research. Future systematic reviews employing broader or alternative search strategies may uncover additional relevant studies and provide more comprehensive insights.

6.1 Operations

In recent years, PL operations have attracted growing academic and practical interest. However, several gaps in the existing literature remain, which limits a comprehensive understanding of the full potential and challenges associated with PL systems. First, while many studies emphasize cost reduction through the integration of technology and optimization of PL locations and delivery routes, there is a lack of review on the long-term economic benefits and potential risks of these strategies, particularly in terms of reliability and robustness under uncertain demand conditions. More research is also needed on the dynamic behavior of PL systems. Existing studies largely address spatial and temporal dynamics and uncertain consumer demand, but offer limited insight into how urban mobility can be effectively integrated with environmental sustainability goals.

Although some research has investigated the location problem of PLs and examined location strategies and their operational implications, a comprehensive analytical framework is still lacking. Moreover, the integration of PL systems with public transportation infrastructure remains underexplored. Although some studies have evaluated the placement of CDP in public venues such as supermarkets, service stations, and post offices to better understand e-consumer preferences (El Moussaoui et al., 2022), more work is needed to assess the broader implications of this integration for system efficiency and accessibility. Within our literature search parameters, current research predominantly emphasizes the distribution and usage patterns of PLs in urban contexts, whereas relatively few comprehensive analyses were found explicitly addressing rural deployment and utilization. This observation does not mean that such research is completely missing, but it shows that more studies are needed on rural and regional differences. In particular, comparing results across different cultures could be a useful direction for future research.

Most research on PL has focused on APL, particularly in the context of location optimization. Although MPLs offer a promising alternative for last mile delivery, existing studies primarily focus on optimizing MPL delivery routes. Comparative analyses between MPL and APL remain limited and underexplored. Moreover, the lack of differentiation between attended and non-attended PL models in existing literature may contribute to the limited development of preference-based models (such as Structural Equation Modeling) and structural design frameworks. Future research should explicitly distinguish between these service modes to explore their implications for user behavior, operational efficiency, and system design. Finally, existing studies have discussed the physical attributes and modular design of PLs to suit different environments and user needs, but more exploration is needed in terms of innovative design. To enhance the efficiency of PL operations, several avenues for optimization and innovation can be explored. Future research should focus on resource scheduling, location selection, intelligent design, consumer demands, and integration with urban infrastructure to maximize the benefits of PL systems. Optimal resource scheduling and location selection for PL systems need further exploration.

Given the limitations related to the selection criteria, database coverage, and keyword specificity of this review, certain operational topics were found to be relatively underrepresented. These include dynamic relocation and MPL scheduling, integration with public transportation infrastructure, and systematic assessments in rural or underserved areas. This does not imply a complete absence of scholarly work in these areas, but points to the need for more empirical, interdisciplinary, and policy-oriented research to address these emerging operational challenges.

Moreover, although many studies present advanced optimization frameworks for PL operations, including location planning, routing efficiency, and service clustering, a disconnect often persists between these models and the practical challenges of real-world deployment. Effective implementation requires considering regulatory constraints, stakeholder coordination, infrastructure limitations, and varying levels of technological readiness. Therefore, future research should focus on developing adaptive and scalable operational strategies that respond to diverse urban contexts and policy frameworks, supported by empirical validation in actual logistic systems.

6.2 Sustainability impact

Although PLs have shown potential for delivery efficiency, there are still significant gaps in understanding their broader economic, environmental, and social impacts on sustainability.

In terms of economic sustainability, although many studies have focused on the cost optimization and profitability of PL systems, there is a lack of systematic research on multidimensional cost-benefit analysis and long-term economic impact. Most studies conduct a cost analysis from a single perspective and lack a comprehensive life cycle cost analysis, including initial investment, technology upgrades, maintenance, and operational costs. In addition, there is a lack of research on cost changes under uncertain demand and market fluctuations. Existing research focuses primarily on reducing operating and delivery costs through technology integration and optimizing PL locations, but lacks an assessment of long-term economic benefits and potential risks. For example, there is insufficient research on maintaining low costs in the long term under various market conditions and limited analysis on the applicability to enterprises of different sizes.

For environmental sustainability, research has focused mainly on the impact of PLs on GHG emissions and operational practices, while there is limited in-depth analysis of energy efficiency and resource utilization. Although environmental benefits such as reduced GHG emissions and optimized resource utilization have been discussed in several studies, systematic and long-term environmental impact assessments of PL systems across diverse urban contexts remain relatively limited in the existing literature reviewed here. Specifically, the long-term impact of PLs on improving urban quality of life and promoting sustainable urban development has not been thoroughly confirmed through empirical data. This suggests that future research could offer valuable insights by conducting longitudinal evaluations of environmental effects across different urban and regional settings.

While social dimensions such as customer convenience, service safety, and user satisfaction have been addressed to some extent in existing studies, the literature identified within this review generally prioritizes economic and environmental impacts more extensively. A deeper and broader exploration of social values, especially through systematic empirical studies, appears to be limited in our selected literature. Therefore, future research efforts are encouraged to expand the scope and depth of investigations into these social dimensions to fully capture the multidimensional benefits of PL systems. The extent to which PL systems contribute to improving quality of life has not been thoroughly evaluated. Few studies have addressed the fairness and accessibility of PLs in different socioeconomic groups, and research on their application in low-income communities and remote areas is still insufficient. Furthermore, the application of PL in nontraditional retail industries has received relatively little scholarly attention. Current research focuses primarily on the retail and e-commerce sectors, with comparatively fewer studies exploring the use of PL in areas such as second-hand goods trading, drug delivery, and library services.

It is important to reflect on why certain sustainability-related dimensions, particularly those concerning long-term environmental assessment, equitable access, and nontraditional service applications, appear underrepresented in the literature we reviewed. This gap may be attributed in part to our focus on operationally oriented peer-reviewed studies and the defined database search strategy, which may have excluded interdisciplinary or policy-oriented work outside of the main logistics outlets. Furthermore, the novelty of some of these dimensions (e.g., the use of PL in second-hand markets or marginalized communities) suggests that empirical research is still in its early stages of development. Rather than interpreting these omissions as evidence of a complete lack of academic attention, we see them as an opportunity for future investigations to explore these under-examined, yet crucial, facets of PL sustainability.

6.3 AI applications

The application of AI technology in PL systems has been mainly limited to models and algorithm optimization, with fewer practical applications and empirical case studies. There is a lack of comprehensive empirical research on how to better integrate AI technology into existing logistics systems, as well as its effects and challenges in actual operations. In terms of dynamic monitoring and real-time adjustment of PL delivery network layouts, relevant application research on AI technology is still in its initial stage, with a lack of in-depth discussion on its practical effects and long-term impact. For demand forecasting and resource optimization management, although many studies focus on how to use AI technology for effective management, more verification is needed regarding the adaptability and reliability of these technologies in complex and uncertain environments. Additionally, although AI technology is used to optimize user experience, there is limited research on personalized demand analysis and service optimization for different user groups, and a lack of systematic evaluation and empirical research on AI's role in improving user satisfaction, usage frequency, and overall service quality.

Future research should focus on integrating AI into existing logistics systems and validating its impact through real-world applications. By combining AI technology, PLs can intelligently and dynamically adjust their storage space to accurately match the needs of various users. This design strategy can significantly improve the user experience while also promoting environmental protection and resource conservation, aligning with principles of sustainable development. Such design innovations can lead to a more intelligent, humane, and environmentally friendly development of PL systems.

First, beyond the addition of mobile or foldable designs, AI-based intelligent recognition technology could be introduced, allowing PLs to automatically identify and classify packages of different sizes. This design would reduce the error rate of manual operation and improve PL efficiency. Moreover, by analyzing usage data with AI algorithms, future predictions on the number and size distribution of packages could help optimize storage space allocation in advance.

Second, a more user-friendly interactive interface can be designed to further enhance the user experience. For example, using a touchscreen or mobile app, users could query package storage locations, estimated retrieval times, and other information in real-time, as well as schedule pickup appointments and use QR codes for pickup. For special user groups, such as the elderly and disabled, features like voice prompts and large font displays can ensure accessibility.

Future research should also explore the combined application of queueing theory and AI technology. Queueing theory provides a theoretical basis for optimizing service processes and reducing waiting times, while AI technology enhances system flexibility and responsiveness through intelligent prediction and real-time adjustments. For APLs, AI can monitor and manage PL usage in real time, dynamically adjusting service strategies to improve operational efficiency. For MPLs, AI technology, combined with queueing theory, can optimize dynamic scheduling and location selection, ensuring sufficient service capabilities in high-demand areas and meeting diverse user needs.

The scarcity of empirical research and practical applications observed in supporting AI-based PL systems requires a critical examination of the root causes of this research gap. This phenomenon may be attributed in part to our methodological focus on the operational logistics literature, which may systematically exclude AI-related research rooted in human-computer interactions, information systems, or behavioral disciplines. Furthermore, the application of AI in PL systems, especially in environments where real-time optimization and personalized services are required, remains an emerging research boundary, with theoretical claims often preceding practical implementation and empirical verification. We therefore interpret this as having no academic focus, but rather an opportunity to conduct interdisciplinary research promptly that can bridge the paradigms of logistics, AI, and human-centered design.

Beyond theoretical model development, future research should place greater emphasis on empirical studies that reflect the perspectives of diverse stakeholders, including logistics service providers, local governments, urban planners, property managers, and end-users. A detailed understanding of their goals, constraints, and incentives is essential for the practical implementation of PL systems. Furthermore, evaluating PL deployment under real-world conditions, such as within existing regulatory frameworks, physical space limitations, and cost–benefit considerations, can help bridge the gap between academic models and practical feasibility. A stakeholder-driven and context-sensitive research approach will provide more insight into adoption barriers, operational challenges, and effective strategies for sustainable integration.

7 Conclusion

This literature review has provided a comprehensive overview of current research on PL solutions for last mile delivery. It also addresses key operational challenges, sustainability implications, and the emerging role of AI in improving PL systems. Through a systematic review of existing studies, it becomes clear that PLs represent a promising solution for addressing some of the complexities of last mile logistics. More specifically, PLs offer important advantages such as improved delivery efficiency, lower operational costs, and increased customer satisfaction. In addition, they contribute to broader sustainability goals by reducing GHG emissions and reducing urban traffic congestion.

The operational problems associated with PL are mainly focused on optimizing its location, delivery routes, and integration within existing logistics networks. Most studies on PLs have explored location optimization, especially with the aim of minimizing costs, improving delivery efficiency, and reducing delivery failures. In addition, a limited number of studies have examined other key operational challenges, such as dealing with stochastic demands, addressing capacity constraints, and integrating PL with various delivery systems. Although progress has been made in these areas related to PL, particularly through mathematical modeling and simulation, future research should emphasize more dynamic approaches capable of capturing real-time variables in both urban and rural environments.

The sustainable impacts of PL are multifaceted and include economic, environmental, and social aspects. Economically, PLs have shown the potential to optimize logistics costs and increase profitability. Cost-benefit analyses indicate that PL systems can streamline delivery operations by centralizing drop-off points and minimizing failed delivery attempts, thus reducing vehicle mileage, fuel consumption, and overall delivery times. The operational efficiency of the PL system, especially through the strategic placement of lockers and the integration of advanced technologies, improves the scalability and sustainability of last mile logistics networks. This review also emphasizes the environmental benefits of PL systems, primarily by reducing GHG emissions and improving resource efficiency. PL systems substantially reduce the environmental impact of last mile logistics by consolidating deliveries into fewer trips. However, the magnitude of these benefits varies depending on geographic and demographic factors, with greater environmental advantages typically observed in urban areas compared to rural regions with lower population densities. From a social sustainability perspective, PLs improve convenience and accessibility for consumers by offering flexible and secure parcel retrieval options, a feature that is increasingly important in the era of e-commerce. In addition, the PL system supports equitable access to logistics services, especially in urban areas experiencing traffic congestion and delivery bottlenecks. Despite these benefits, more research is necessary to fully understand the potential of PL in low-income and low-density regions.

The application of AI in PL is still in its early stages, yet the optimization potential of AI technology for PL systems is considerable. AI can be used for demand forecasting, route optimization, and dynamic locker allocation based on real-time demand patterns. In particular, machine learning algorithms can improve the user experience by predicting consumer preferences, thus optimizing locker locations and capacity as needed. Additionally, AI enables the design and adaptation of interactive PL interfaces tailored to user requirements, promoting flexibility and broad applicability of PL solutions.

Overall, PLs represent a transformative solution to the challenges of last mile delivery, with operational, sustainability, and technological advantages. To address operational challenges in terms of layout, capacity, and routing, PL systems have proven to be economically and environmentally sustainable while providing greater convenience for consumers. As urban populations grow and e-commerce continues to expand, the role of PL systems in building resilient and efficient logistics networks will become increasingly important. Continued innovation, particularly in the integration of AI, user interface development, and system scalability, will be essential to fully realize the potential of PLs across various geographic and socio-economic settings.

Author contributions

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