



Multi-Objective Optimization for Sustainable Production Systems: A Qualitative Systematic Literature Review of Routing Models, Efficiency, and Sustainability Performance

Indra Saputra¹, Grace Yulianti²

¹STIE Kasih Bangsa, Indonesia, indrasaputra@stiekasihbangsa.ac.id

² STIE Kasih Bangsa, Indonesia, grace@stiekasihbangsa.ac.id

ABSTRACT. *This study presents a qualitative systematic literature review of multi objective optimization for sustainable production systems, focusing on production routing models, computational efficiency, and sustainability performance. The review synthesizes research on the integration of production, inventory, distribution, and routing decisions and examines the incorporation of economic, environmental, and social objectives into optimization models. Using a systematic search and screening approach guided by PRISMA principles, the study identifies major methodological developments, sustainability indicators, optimization techniques, and research gaps. The findings indicate a progressive shift from cost oriented production routing models toward integrated multi objective frameworks that address sustainability trade offs. Economic performance remains the most established dimension, while environmental performance is increasingly incorporated through emissions and fuel consumption measures. Social sustainability remains comparatively underdeveloped, particularly regarding quantitative safety and accident risk indicators. The review highlights Pareto based approaches, including weighted sum and AUGMECON2 methods, as important tools for balancing competing objectives. The study proposes future research directions emphasizing scalable, integrated, and triple bottom line optimization models.*

Keywords *Multi objective optimization; Sustainable production systems; Production routing; Sustainability performance; Pareto optimization*

INTRODUCTION

Sustainable production systems increasingly require decision making approaches that simultaneously address economic efficiency, environmental protection, and social responsibility. Production, inventory, distribution, and transportation decisions are highly interdependent, and optimizing them separately may create locally efficient but globally inefficient outcomes. This challenge is central to the Production Routing Problem (PRP), which integrates production planning, inventory management, product distribution, and vehicle routing within a unified framework. The PRP determines production quantities and timing, inventory levels, customer service, and transportation decisions over a planning horizon (Adulyasak et al., 2015).

Conventional production and routing optimization has primarily focused on minimizing operational costs, including production, setup, inventory, transportation, and routing expenses. However, the increasing complexity of supply chains shows that economic efficiency alone is insufficient for evaluating modern production systems. Hrabec et al. (2022), through a systematic review and meta-analysis, found that integrated production, inventory, and routing planning can generate substantial economic benefits,

with an estimated cost saving of approximately 11.08% compared with sequential planning. This finding highlights the value of treating operational decisions as an interconnected system. Effective corporate governance and sustainable leadership will help a company perform much better (Kusnanto, E., 2022).

Sustainability considerations have also transformed production and routing optimization by incorporating environmental concerns such as fuel consumption, greenhouse gas emissions, and resource use. Bektaş and Laporte (2011) demonstrated that vehicle emissions are influenced not only by travel distance but also by vehicle load, speed, fuel consumption, and travel time. Their Pollution-Routing Problem expanded conventional routing models by integrating environmental impacts into operational decisions. Sustainability, innovation, and dynamic factors are important capabilities for multi-finance companies that need to be strengthened and developed (Patricia, M. C, 2023).

These findings are particularly relevant to integrated production-routing systems because production quantities, inventory levels, shipment sizes, vehicle selection, and delivery routes jointly influence both operational performance and environmental impact. Consequently, sustainable production systems require integrated optimization models that balance economic efficiency with broader sustainability objectives. The operational resilience influences corporate sustainable longevity directly and indirectly through innovation performance (Thoha et al., 2021).

Research on production and inventory routing demonstrates that economic and environmental objectives may conflict. Darvish et al. (2019) showed that solutions minimizing operational costs do not necessarily minimize emissions, as production, inventory, and transportation decisions produce different outcomes depending on whether economic efficiency or environmental performance is prioritized. Sustainable production systems therefore require optimization approaches that explicitly represent such trade-offs.

This transition is also reflected in sustainable inventory-routing research. Malladi and Sowlati (2018), in their review of 40 studies, identified growing attention to emissions, reverse logistics, waste reduction, and product perishability. However, sustainability-oriented research remained limited compared with economically focused

routing studies, with environmental objectives receiving substantially greater attention than social objectives.

The social dimension remains a major challenge because factors such as occupational safety, accident risk, employment, worker well-being, and community impacts are difficult to quantify within mathematical models. Messmann et al. (2020), reviewing 91 studies, found that quantitative social indicators were considerably less developed than environmental indicators. This limitation makes the integration of social sustainability into production-routing optimization an important research frontier.

This gap is significant because production and transportation decisions may create safety risks not captured by conventional cost or emissions objectives. A low-cost production facility may expose workers to greater accident risks, while transportation strategies designed to reduce fuel or vehicle costs may generate different safety implications. Therefore, economically or environmentally optimal solutions may not necessarily be socially optimal, highlighting the importance of simultaneously considering economic, environmental, and social performance.

Recent research demonstrates progress toward this multidimensional perspective. Garside et al. (2025) proposed a multi objective mixed integer linear programming model for sustainable production routing that integrates total operational cost, emissions cost, and social accident cost. The model incorporates accidents in production, handling, and transportation, vehicle-related emission parameters, multiple plants and products, and a heterogeneous fleet.

The multi objective nature of sustainable production systems creates additional methodological challenges because improvements in one sustainability dimension may reduce performance in another. Rather than identifying a single optimal solution, decision-makers require Pareto efficient alternatives that reveal trade offs among competing objectives. Multi objective optimization provides an appropriate framework by simultaneously optimizing conflicting objectives according to different strategic priorities.

Among available approaches, the weighted-sum method is widely used because of its simplicity, although its effectiveness depends on objective weights and may have limitations in representing non-convex Pareto frontiers. Alternatively, the augmented ϵ -constraint approach generates Pareto solutions by optimizing one objective while

constraining others. Mavrotas and Florios (2013) developed AUGMECON2 to efficiently identify exact Pareto sets in multi objective integer programming, making comparisons between these approaches important for evaluating solution quality and diversity.

Against this background, the present qualitative systematic literature review examines the evolution of multi objective optimization for sustainable production systems, focusing on production-routing models, computational efficiency, and sustainability performance. The review analyzes how economic, environmental, and social objectives are formulated; how production, inventory, transportation, and routing decisions are integrated; which sustainability indicators are applied; and which exact, heuristic, metaheuristic, and hybrid approaches are used.

The study also addresses fragmented evidence across production routing, inventory routing, green vehicle routing, and sustainable supply chain optimization. Previous reviews have examined PRP formulations and algorithms (Adulyasak et al., 2015), integrated planning benefits (Hrabec et al., 2022), sustainable inventory routing (Malladi & Sowlati, 2018), and social-impact quantification (Messmann et al., 2020). However, the convergence of multi objective optimization, production routing, and the simultaneous economic, environmental, and social dimensions remains insufficiently synthesized.

Accordingly, this review identifies dominant research themes, methodological developments, sustainability indicators, optimization strategies, and unresolved gaps in multi objective sustainable production routing research. It positions sustainable production routing as a strategic decision problem involving competing economic, environmental, and social priorities, while identifying opportunities for more integrated, transparent, and practically applicable sustainable production systems.

LITERATURE REVIEW

The Production Routing Problem (PRP) has emerged as an important integrated supply chain optimization problem because it simultaneously coordinates production, inventory, distribution, and vehicle routing decisions across a planning horizon (Adulyasak et al., 2015). The integration of these decisions is theoretically important because production quantities determine available inventory, inventory decisions influence shipment quantities, and shipment quantities subsequently determine vehicle

utilization and routing requirements (Adulyasak et al., 2015). Unlike sequential planning, in which production, inventory, and transportation decisions are optimized independently, an integrated PRP attempts to identify a system level solution that considers the interdependence among these activities (Hrabec et al., 2022).

The systematic review and meta analysis conducted by Hrabec et al. (2022) provides strong empirical evidence for the value of integrated planning, as their analysis of 20 relevant studies and computational results from 15 studies estimated an average cost saving of 11.08%, with a 95% confidence interval of 6.58%–15.58%, when production, inventory, and routing were integrated rather than planned sequentially. This finding indicates that integration is not merely a modeling preference but can generate measurable operational efficiency improvements. However, the traditional PRP literature has primarily emphasized economic efficiency, particularly the minimization of production, setup, inventory, and transportation costs, rather than simultaneous consideration of broader sustainability performance (Darvish et al., 2019).

The computational complexity of PRP has encouraged the development of a broad range of exact, heuristic, metaheuristic, and hybrid solution procedures (Adulyasak et al., 2015). Solyalı et al. (2017), for example, developed a multi-phase mathematical-programming-based heuristic and reported that it generated new best solutions for approximately 65% of the benchmark instances examined. Li et al. (2019) subsequently addressed a large scale multi product PRP with outsourcing and tested their three-level heuristic on 225 newly generated instances, while also evaluating 1,530 classical PRP benchmark instances. Their results demonstrated the ability of the proposed heuristic to obtain high-quality solutions for large scale instances within relatively short computational times, illustrating the continuing importance of computational efficiency in PRP research.

The PRP literature has progressively expanded from relatively simple single product and single plant configurations toward richer production routing structures involving multiple products, multiple periods, outsourcing, heterogeneous fleets, perishability, transshipments, and operational constraints (Adulyasak et al., 2015; Li et al., 2019). This development reflects the recognition that realistic production systems contain heterogeneous resources and complex interactions that cannot be adequately represented by simplified routing models (Fortes et al., 2022).

Fortes et al. (2022) examined a rich production routing problem incorporating limited production and storage capacities, heterogeneous vehicles, maximum vehicle riding time, and back orders, and proposed three hybrid two level decomposition approaches to address the rapidly increasing problem size. Their findings demonstrate that operational level decomposition and hybrid mathematical approaches can remain effective when the number of customers, periods, products, and vehicles substantially increases. Similarly, Alvarez et al. (2022) extended PRP to perishable products with fixed shelf life and gradual decay, formulated the problem as a mixed integer linear program, and developed branch and cut and hybrid iterated local search approaches. Their results showed that increasing product decay rates reduced total profit through both lower revenues and higher costs, demonstrating that product characteristics can fundamentally alter production routing decisions.

Uncertainty is another important extension of PRP models because demand variability can make deterministic production and routing plans less robust (Agra et al., 2018). Agra et al. (2018) formulated a stochastic production inventory routing problem in which production and routing decisions were determined before demand scenarios were revealed, whereas delivery quantities and inventory levels could subsequently adapt to realized scenarios. Their hybrid approach combined sample average approximation and relax and fix strategies and showed better performance than the classical sample approximation method on difficult randomly generated instances. These findings suggest that sustainable production-routing models should increasingly incorporate uncertainty rather than assuming that demand, transportation conditions, and production requirements are perfectly known.

A major transition in the literature has been the movement from cost-oriented PRP toward green and sustainable production routing models (Darvish et al., 2019). Darvish et al. (2019) explicitly compared economic and environmental objectives in production and inventory routing systems and demonstrated that operational decisions can generate substantially different outcomes depending on whether the system minimizes costs or emissions. Their results therefore demonstrate that cost minimization cannot automatically be interpreted as environmental efficiency.

The environmental dimension is particularly relevant to transportation because emissions are affected by several operational characteristics, including travel distance,

vehicle load, speed, and fuel consumption (Bektaş & Laporte, 2011). The Pollution Routing Problem introduced by Bektaş and Laporte (2011) established an important methodological foundation by explicitly integrating vehicle routing decisions with pollution and fuel consumption considerations. This perspective is particularly relevant to PRP because production quantities and inventory decisions influence shipment quantities and therefore affect vehicle loads and transportation emissions.

Qiu et al. (2017) further integrated environmental regulation into PRP by developing a production routing model under carbon cap and trade, with carbon emissions incorporated into production, inventory, and routing decisions. Their branch and price approach was based on Dantzig Wolfe decomposition and column generation, while computational results provided insights into the relationship between carbon regulation, lost sales, transportation decisions, and emissions reduction. This study demonstrates that environmental policy mechanisms can be incorporated directly into production routing optimization rather than being treated as external constraints.

More recent research has examined explicit trade offs between total cost and total emissions in production inventory routing systems (Sun et al., 2023). Sun et al. (2023) developed models for multiple perishable products and multiple vehicles and found that transportation was the most influential activity for the two investigated models in terms of the economic environmental trade off. Their model also represented transportation emissions as dependent on vehicle load, velocity, and traveled distance, confirming that environmental performance cannot be captured adequately by distance alone.

Peivastehgar et al. (2023) extended this environmental perspective to a green production routing problem for medical nitrous oxide and formulated a bi objective model that minimized total cost and greenhouse gas emissions under a heterogeneous delivery fleet. Their research is particularly relevant because it demonstrates the feasibility of combining production emissions and transportation emissions within a single PRP framework.

The growing recognition that economic and environmental objectives may conflict has encouraged the application of multi objective optimization to sustainable supply chain and routing problems (Darvish et al., 2019). Instead of producing one solution based on a single objective, multi objective optimization generates alternative solutions

representing different trade offs among competing objectives, thereby providing decision makers with greater flexibility (Abdullahi et al., 2021).

Abdullahi et al. (2021) provide particularly relevant evidence because their sustainable vehicle routing model simultaneously considered economic, environmental, and social sustainability dimensions. They developed both weighted sum and ϵ -constraint formulations and combined these with a biased randomized iterated greedy algorithm to solve the integrated sustainability problem. Their sensitivity analysis demonstrated the importance of evaluating trade offs among sustainability dimensions and showed the usefulness of posteriori weighting for supporting sustainability oriented decisions.

The use of multiple objectives also requires appropriate performance indicators for evaluating the quality of Pareto solutions (Audet et al., 2021). Common indicators in multi objective optimization include measures of convergence, diversity, spacing, and distance from the ideal or reference Pareto front, which enable researchers to compare alternative algorithms beyond computational time alone (Audet et al., 2021). This is important for sustainable production routing research because an algorithm that obtains one strong solution may nevertheless perform poorly in generating a diverse and representative Pareto frontier.

Although environmental objectives have become increasingly prominent, the social dimension remains comparatively underdeveloped in quantitative supply chain optimization (Messmann et al., 2020). Messmann et al. (2020) systematically reviewed 91 studies on social impacts in strategic supply chain optimization and concluded that quantitative social indicators and assessment methods had not developed to the same level as environmental indicators. Their review also found that employment creation was frequently used as the primary social indicator, while studies incorporating multiple social indicators often aggregated them into a generic weighted social score.

This limitation is important for production routing research because social sustainability may involve occupational safety, accident risk, employee well being, workload, and transportation related risks, all of which can influence the sustainability performance of production and logistics systems (Messmann et al., 2020). Social indicators are therefore required to move sustainable PRP beyond the traditional combination of cost and emissions. The literature indicates that social performance should

increasingly be treated as an explicit optimization objective rather than merely a qualitative consideration (Messmann et al., 2020).

The integration of economic, environmental, and social objectives represents the most comprehensive direction of sustainable production routing research (Abdullahi et al., 2021; Messmann et al., 2020). Nevertheless, research that simultaneously integrates all three dimensions directly into a PRP remains relatively limited compared with studies focusing on only economic or economic environmental objectives (Garside et al., 2025).

Garside et al. (2025) provide a significant recent contribution by developing a multi objective mixed integer linear programming (MOMILP) model for a sustainable production routing problem incorporating three conflicting objectives: total operational cost, total emissions cost, and total social cost of accidents. Their model explicitly considers social accident costs associated with production, handling, and transportation and incorporates multiple vehicle related parameters in the estimation of transportation emissions. Importantly, the study considers multiple plants, multiple products, and a heterogeneous fleet, thereby representing a richer production routing configuration than many earlier sustainability models.

Garside et al. (2025) compared two exact multi objective approaches, namely the weighted sum method and Augmecon2, to generate Pareto-optimal solutions. Their computational results indicated that Augmecon2 outperformed the weighted-sum approach according to the reported spacing, inverted generational distance, and mean ideal distance measures, with performance efficiencies of 76.12%, 15.32%, and 15.99%, respectively. The findings also revealed a trade off between operational cost and social accident cost, because production facilities with higher setup and production costs but lower injury risks can generate different social cost outcomes. Similarly, the use of larger capacity vehicles may reduce fixed and fuel related costs while increasing transportation related safety risks, illustrating the complex interaction between economic and social sustainability objectives.

The methodological relevance of Augmecon2 originates from the work of Mavrotas and Florios (2013), who developed an improved augmented ϵ -constraint method for obtaining the exact Pareto set in multi objective integer programming. Compared with simple weighted sum formulations, ϵ -constraint methods allow selected objectives to be optimized while alternative objectives are controlled through explicit bounds, which can

be particularly useful when objective functions have different units and conflicting priorities (Mavrotas & Florios, 2013).

The systematic synthesis of the literature indicates that PRP research has developed through several identifiable stages, beginning with integrated economic optimization, followed by richer operational formulations, environmental extensions, and more recently multidimensional sustainability optimization (Adulyasak et al., 2015; Darvish et al., 2019; Garside et al., 2025). The first stage established the value of integrating production, inventory, and routing decisions, with later evidence demonstrating measurable efficiency gains from integrated planning (Hrabec et al., 2022). The second stage expanded the structural complexity of PRP by introducing multiple products, outsourcing, perishability, heterogeneous fleets, stochastic demand, and other operational characteristics (Agra et al., 2018; Li et al., 2019; Alvarez et al., 2022; Fortes et al., 2022).

The third stage introduced environmental objectives, particularly carbon emissions and fuel consumption, and demonstrated that minimizing economic cost does not necessarily produce environmentally optimal solutions (Darvish et al., 2019; Qiu et al., 2017). The fourth stage introduced explicit multi objective formulations in which economic, environmental, and social objectives could be analyzed simultaneously (Abdullahi et al., 2021). The most recent development is the integration of all three sustainability dimensions directly into a production routing MOMILP, as demonstrated by Garside et al. (2025).

Despite these advances, the literature reveals several persistent gaps. First, most PRP studies remain strongly oriented toward economic performance, while social indicators are less frequently quantified than economic and environmental indicators (Messmann et al., 2020; Darvish et al., 2019). Second, many sustainability studies focus on transportation or vehicle routing rather than simultaneously integrating production, inventory, and routing decisions within a single sustainability framework (Abdullahi et al., 2021). Third, realistic PRP characteristics such as multiple plants, multiple products, heterogeneous fleets, perishability, uncertainty, and safety risks substantially increase model complexity and therefore require more efficient exact and hybrid solution approaches (Fortes et al., 2022; Garside et al., 2025).

The literature therefore demonstrates a clear transition from single objective cost minimization toward multi objective sustainability optimization, but this transition

remains fragmented across production routing, inventory routing, vehicle routing, and sustainable supply chain research streams (Adulyasak et al., 2015; Malladi & Sowlati, 2018; Abdullahi et al., 2021). Existing reviews have separately examined PRP formulations and algorithms, sustainability in inventory routing problems, integrated production inventory routing planning, and quantitative social impacts, but a focused synthesis connecting routing models, algorithmic efficiency, Pareto optimization, and simultaneous economic environmental-social performance remains necessary (Adulyasak et al., 2015; Malladi & Sowlati, 2018; Hrabec et al., 2022; Messmann et al., 2020).

Accordingly, the present qualitative systematic literature review positions itself at the intersection of multi objective optimization, production routing models, computational efficiency, and sustainability performance. The review examines how previous studies formulate production routing problems, which economic, environmental, and social indicators are incorporated, how trade offs among sustainability dimensions are represented, which optimization algorithms are employed, and how algorithmic performance is evaluated (Adulyasak et al., 2015; Abdullahi et al., 2021; Garside et al., 2025). Particular attention is given to the evolution from conventional mathematical programming and heuristic methods toward multi objective exact methods such as weighted sum and augmented ϵ -constraint approaches, as well as hybrid and metaheuristic approaches designed to address large and complex instances (Mavrotas & Florios, 2013; Garside et al., 2025).

Overall, the reviewed evidence suggests that future sustainable production systems require models that do not treat economic efficiency, environmental responsibility, and social safety as independent considerations but instead represent them as interconnected and potentially conflicting objectives (Abdullahi et al., 2021; Garside et al., 2025). Such models can provide decision makers with Pareto efficient alternatives that make the consequences of different production, inventory, vehicle, and routing decisions more transparent (Garside et al., 2025). Therefore, the central research opportunity identified by this systematic review is the development of increasingly integrated, computationally efficient, and empirically grounded multi objective optimization models capable of simultaneously improving operational efficiency and sustainability performance across the economic, environmental, and social dimensions.

METHODS

This study adopts a Qualitative Systematic Literature Review (QSLR) to identify, evaluate, categorize, and synthesize previous research on multi-objective optimization for sustainable production systems, focusing on production routing models, computational efficiency, and economic, environmental, and social sustainability. A systematic review enables fragmented knowledge to be consolidated, research patterns identified, methodological developments assessed, and future research directions established (Snyder, 2019). Unlike narrative reviews, it uses explicit and reproducible procedures to reduce arbitrary selection and researcher bias (Tranfield et al., 2003; Snyder, 2019).

The review follows the PRISMA 2020 framework covering identification, screening, eligibility, and inclusion (Page et al., 2021). Seven research questions address the evolution of production routing models, operational characteristics, sustainability indicators, optimization approaches, computational efficiency, sustainability trade-offs, and remaining research gaps.

The literature search focused on production routing, inventory routing, vehicle routing, multi-objective optimization, and sustainability. Keywords included “production routing problem,” “inventory routing,” “multi-objective optimization,” “Pareto optimization,” “e-constraint,” “AUGMECON2,” “sustainable production,” and “green routing,” complemented by terms related to carbon emissions, social costs, heterogeneous fleets, multiple plants, and multiple products. Eligible studies were peer-reviewed English publications addressing production or routing optimization through mathematical programming or related operations research methods and incorporating at least one sustainability dimension. Duplicates, irrelevant studies, editorials, and publications with insufficient methodological information were excluded.

A structured extraction framework recorded bibliographic information, problem characteristics, production, inventory and transportation features, sustainability dimensions, optimization methods, performance measures, findings, and research gaps. The evidence was synthesized through qualitative thematic analysis focusing on: (1) production routing model evolution, (2) sustainability integration, (3) multi-objective optimization approaches, (4) computational efficiency and solution quality, and (5) sustainability trade-offs and managerial implications (Snyder, 2019).

Particular attention was given to weighted-sum, ϵ -constraint, AUGMECON2, heuristic, metaheuristic, matheuristic, and hybrid methods. AUGMECON2 was specifically examined because it is designed to generate exact Pareto solutions for multi-objective integer programming problems (Mavrotas & Florios, 2013). Sustainability was assessed using the triple bottom line: economic indicators such as production, inventory, transportation, and fuel costs; environmental indicators including CO₂ emissions and carbon costs; and social indicators such as accident risk, occupational safety, employment, and social costs.

Computational performance was evaluated through computational time, problem size, optimality gaps, scalability, and solution quality, including spacing, inverted generational distance (IGD), mean ideal distance (MID), hypervolume, convergence, and diversity where reported. The synthesis develops a conceptual framework linking routing model characteristics $\rightarrow$ optimization methodology $\rightarrow$ computational efficiency $\rightarrow$ sustainability performance, highlighting trade-offs among economic, environmental, and social objectives.

Although limitations include English-language restrictions, database coverage, researcher interpretation, and heterogeneity among models, systematic search, screening, extraction, and synthesis procedures enhance transparency and review credibility (Snyder, 2019; Page et al., 2021).

RESULTS

This study applied predefined inclusion and exclusion criteria to ensure the relevance and quality of the selected literature. Eligible studies were peer-reviewed publications addressing production routing, production-inventory routing, inventory routing, vehicle routing, or related supply chain optimization problems. Studies were required to apply optimization or operations research methods, address at least one sustainability dimension or sustainability trade-off, and provide sufficient methodological information for qualitative synthesis. Studies unrelated to the research scope, duplicates, editorials, or publications lacking methodological detail were excluded.

The identification and screening procedure followed the four stages of PRISMA 2020: identification, screening, eligibility, and inclusion (Page et al., 2021). Retrieved records were consolidated, duplicates removed, and titles and abstracts screened for

relevance. Potentially relevant full-text studies were subsequently assessed according to predefined criteria, with the process documented through a PRISMA flow diagram to ensure transparency.

Methodological quality was assessed qualitatively through five dimensions: clarity of research objectives, transparency of mathematical formulation, appropriateness of optimization methods, transparency of computational experiments or validation, and clarity of findings and limitations. Particular attention was given to decision variables, objective functions, constraints, sustainability indicators, assumptions, datasets, benchmark instances, and solution procedures. This approach supports the systematic assessment of evidence quality and methodological transparency (Tranfield et al., 2003; Snyder, 2019).

A structured data-extraction framework was used to code bibliographic characteristics, problem structures, production and transportation features, sustainability dimensions, optimization approaches, computational performance, principal findings, and research gaps. This systematic coding enabled comparisons across heterogeneous studies and supported thematic synthesis.

Sustainability performance was analyzed using the triple-bottom-line perspective. Economic performance included operational, production, setup, inventory, transportation, and fuel costs, while environmental performance covered CO₂ emissions, greenhouse gas emissions, fuel consumption, carbon costs, and pollution indicators. Social performance included accident risk, occupational safety, employment, and other measurable social impacts. The review also examined whether these dimensions were represented as objectives, constraints, costs, or composite indicators.

Computational efficiency was evaluated through computational time, problem size, optimality gaps, scalability, benchmark instances, and solution quality. Multi-objective studies were further assessed using indicators such as spacing metric, inverted generational distance, mean ideal distance, hypervolume, convergence, and diversity. The review distinguished solution quality from computational efficiency because highly accurate solutions may require substantial computational resources.

To strengthen reliability, search strategies and eligibility criteria were defined before study selection, extracted information was systematically recorded, and interpretations were grounded in the findings of original studies. Competing findings

were retained to reduce selective interpretation and improve transparency (Tranfield et al., 2003; Snyder, 2019; Page et al., 2021).

The final synthesis developed a conceptual framework linking routing-model characteristics → optimization methodology → computational efficiency → sustainability performance. Model characteristics, including multiple plants, products, heterogeneous fleets, capacity, inventory, and delivery constraints, influence mathematical complexity and the selection of exact, heuristic, metaheuristic, matheuristic, or hybrid methods. The selected approach subsequently affects computational efficiency and the ability to generate high-quality Pareto solutions that reveal trade-offs among economic, environmental, and social objectives.

Although the systematic approach improves methodological rigor, limitations remain regarding English-language restrictions, database coverage, researcher interpretation, and heterogeneity across optimization models. Nevertheless, systematic documentation of searching, screening, appraisal, extraction, and synthesis reduces arbitrary selection and enhances the transparency and credibility of the review (Snyder, 2019; Page et al., 2021).

DISCUSSION

The findings of this qualitative systematic literature review show that sustainable production systems have progressively evolved from conventional cost-oriented production-routing optimization toward integrated multi-objective frameworks that simultaneously consider economic, environmental, and social performance. Although the Production Routing Problem (PRP) originally focused on integrating production, inventory, distribution, and vehicle routing, sustainability considerations have substantially expanded its scope (Adulyasak et al., 2015).

First, the review confirms the importance of integrated production, inventory, and routing decisions. Adulyasak et al. (2015) emphasized the need to optimize these activities simultaneously, while Hrabec et al. (2022) estimated an average cost saving of approximately 11.08% from integrated planning compared with sequential decision-making. This indicates that integration forms the operational foundation of sustainable production systems because production and inventory decisions influence shipment quantities, vehicle utilization, transportation requirements, and sustainability outcomes.

Second, economic efficiency and environmental sustainability should not be treated as equivalent objectives. Darvish et al. (2019) demonstrated that alternative production and inventory-routing decisions produce different cost and emissions outcomes. Similarly, Bektaş and Laporte (2011) showed that emissions depend on vehicle load, speed, distance, and fuel consumption. Therefore, production quantities, shipment sizes, fleet characteristics, and routing structures jointly affect both operational costs and environmental performance.

Third, the review finds that multi-objective optimization provides a more appropriate framework for sustainability than single-objective optimization. Abdullahi et al. (2021) jointly modeled economic, environmental, and social dimensions in green vehicle routing, demonstrating that sustainability objectives should be treated as competing priorities. However, the present review shows that recent research increasingly extends this perspective to the more complex integration of production, inventory, and transportation decisions.

The social dimension remains the least developed aspect of sustainable production optimization. Messmann et al. (2020) found that quantitative social indicators and assessment methods were less mature than environmental measures. Consequently, incorporating accident risk, occupational safety, social costs, and worker-related impacts represents an important methodological frontier.

A significant recent advancement is provided by Garside et al. (2025), who developed a multi-objective mixed-integer linear programming model integrating total operational cost, emissions cost, and social accident cost. The model considers accidents in production, handling, and transportation, as well as multiple plants, products, and a heterogeneous vehicle fleet. Compared with previous vehicle-routing studies, this approach extends triple-bottom-line optimization into a richer production-routing environment.

The review also demonstrates that algorithm selection significantly affects sustainability performance. Garside et al. (2025) compared the weighted-sum approach and AUGMECON2, reporting superior performance for AUGMECON2 based on spacing, inverted generational distance, and mean ideal distance. Pareto-oriented methods are therefore valuable because they provide decision-makers with alternative solutions reflecting different sustainability priorities.

Increasing model realism further intensifies computational challenges. Sun et al. (2023) showed that perishability and multiple operational constraints increase the complexity of economic-environmental trade-offs. Similarly, the inclusion of multiple products, plants, heterogeneous fleets, capacity constraints, and sustainability objectives improves practical relevance but substantially increases computational complexity.

Overall, the eight previous studies reveal a clear research trajectory: from integrated PRP foundations and environmental routing toward explicit economic-environmental trade-offs, social sustainability, triple-bottom-line optimization, and advanced multi-objective solution methods. The present review therefore positions sustainable production routing as a multidimensional trade-off problem rather than a conventional cost-minimization problem.

A central remaining challenge is balancing model richness with computational efficiency. More realistic models provide better representations of sustainable production systems but require increasingly advanced optimization procedures. Future research should therefore develop scalable models that integrate rich operational characteristics, reliable social indicators, and efficient Pareto-generation techniques. Such developments can support more balanced and practically applicable decisions by simultaneously addressing operational efficiency, environmental performance, and social responsibility.

CONCLUSION

This qualitative systematic literature review examined the development of multi-objective optimization for sustainable production systems, focusing on production routing models, computational efficiency, and sustainability performance. The findings show a transition from conventional cost oriented Production Routing Problems (PRPs) toward integrated optimization frameworks that simultaneously address economic, environmental, and social objectives. Production, inventory, distribution, and routing are increasingly recognized as interdependent decisions whose joint optimization can improve overall system performance (Adulyasak et al., 2015; Hrabec et al., 2022).

Economic performance remains the most established dimension, typically measured through production, setup, inventory, transportation, and fuel costs. Environmental performance has also become increasingly important through CO₂ emissions, fuel consumption, carbon costs, and pollution related indicators (Bektaş &

Laporte, 2011; Darvish et al., 2019). However, economic and environmental objectives frequently conflict, indicating that cost minimization does not necessarily generate environmentally optimal production routing solutions.

The social dimension remains comparatively underdeveloped. Quantitative indicators related to occupational safety, accident risk, employment, and social impacts are less standardized than economic and environmental measures (Messmann et al., 2020). This represents an important gap because production, handling, and transportation activities can generate significant social and safety consequences that are often overlooked in conventional optimization models.

The review also highlights the growing importance of multi objective optimization. Weighted sum, ϵ -constraint, Pareto-based, and hybrid approaches enable decision makers to evaluate trade offs among competing sustainability objectives rather than combining them into a single measure (Abdullahi et al., 2021; Mavrotas & Florios, 2013). Pareto based approaches are particularly valuable because they provide alternative solutions reflecting different economic, environmental, and social priorities.

Garside et al. (2025) represent a significant recent development by integrating operational cost, emissions cost, and social accident cost within a multi objective mixed integer linear programming model for sustainable production routing. Their model considers multiple plants, multiple products, and a heterogeneous vehicle fleet, while demonstrating the potential advantages of AUGMECON2 over the weighted sum approach in generating Pareto solutions.

Computational efficiency remains a critical challenge because increasing the number of operational variables, constraints, and sustainability objectives substantially raises optimization complexity (Adulyasak et al., 2015). Future research must therefore balance model realism with computational scalability through exact methods, decomposition, matheuristics, metaheuristics, and hybrid approaches.

Overall, sustainable production systems should move toward integrated triple bottom line optimization that simultaneously addresses operational efficiency, environmental impacts, and social responsibility. Future studies should improve the standardization of social sustainability indicators, incorporate realistic operational conditions, and develop transparent Pareto based decision support mechanisms for managers and policymakers.

LIMITATION

Despite its contribution to understanding multi objective optimization for sustainable production systems, this qualitative systematic literature review has several limitations. First, the review is subject to database coverage limitations because systematic reviews depend on selected databases, indexing systems, search engines, and publisher collections. Relevant studies that are not indexed in these sources may have been excluded, potentially affecting the comprehensiveness of the evidence base (Snyder, 2019).

Second, the review focuses primarily on English language scholarly literature, which may exclude relevant studies published in other languages and create geographical or linguistic bias. Therefore, the findings may not fully represent the global literature on sustainable production routing optimization.

Third, the literature shows substantial methodological heterogeneity. Previous studies employ different PRP formulations, assumptions, datasets, planning horizons, fleet structures, sustainability indicators, objective functions, and optimization algorithms. This diversity makes direct quantitative comparisons of computational performance and solution quality difficult.

Fourth, the study adopts a qualitative synthesis rather than a statistical meta analysis. It focuses on identifying patterns, methodological developments, sustainability dimensions, trade offs, and research gaps rather than calculating pooled statistical effects. Therefore, conclusions regarding the superiority of optimization approaches should be interpreted within the context of individual studies.

Fifth, thematic coding and qualitative synthesis involve researcher interpretation. Although predefined research questions, inclusion criteria, and extraction categories were applied to improve consistency, different researchers may classify optimization models or sustainability indicators differently, particularly when terminology overlaps (Snyder, 2019).

Sixth, standardized social sustainability indicators remain limited. While economic indicators such as total cost and environmental indicators such as CO₂ emissions are relatively measurable, social indicators including accident risk, worker safety, employment, and social welfare are more heterogeneous, limiting consistent comparisons across studies (Messmann et al., 2020).

Seventh, many studies rely on benchmark instances, simulated datasets, or numerical experiments rather than extensive real world industrial data. Consequently, optimization results may not fully reflect operational uncertainty, behavioral factors, regulatory requirements, and organizational constraints, potentially limiting external validity.

Finally, the rapidly evolving nature of sustainable production and optimization research presents an additional limitation. Developments in artificial intelligence, digital twins, real time optimization, autonomous systems, carbon accounting, and advanced multi objective algorithms may rapidly change the field.

Despite these limitations, the review provides a structured synthesis of the transition from conventional production routing optimization toward integrated multi objective sustainability models. The underdevelopment of quantitative social indicators, the trade-off between model complexity and computational efficiency, and limited real world validation remain important priorities for future research.

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