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From waste to profit: An environmental, social, and governance (ESG) framework for integrating recycled plastic into sustainable concrete production

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ABSTRACT

The construction sector, a long-standing contributor to global pollution, is increasingly adopting sustainable alternatives to traditional building materials. This study evaluates the use of chemically treated post-consumer plactic packaging waste as a partial cement replacement in concrete production through an environmental, social, and governance oriented analytical framework. We combine life cycle assessment, a bi-objective location-allocation model, and evolutionary game theory to examine the environmental, economic, and governance-related implications of large-scale adoption. The life cycle assessment shows that substituting 3% of cement with treated plastic reduces global warming potential by 15% compared with conventional concrete. The location-allocation model identifies supply chain configurations that balance cost and emissions, while the game-theoretic analysis captures how producers adjust pricing and adoption in response to different governance mechanisms, including subsidies, taxes, and awareness policies. A Canadian case study indicates that, under supportive governance conditions, the share of green producers can increase by up to 63%, demonstrating how coordinated policy interventions can accelerate sustainable transitions. Overall, the results show how integrating environmental assessment, supply chain design, and governance-driven behavioral responses can support the development of more sustainable concrete technologies.

1. Introduction

The construction industry is one of the most significant contributors to the global pollutions, through material extraction, processing, transportation, and use and after-use phases (Benhelal et al., 2013). In terms of materials used, cement is the primary substance used in the construction industry and is widely used in the production of concrete. The production of one ton of Portland cement results in the release of about one ton of CO_2 into the atmosphere, with approximately half originating from the combustion of fossil fuels and the other half from the calcination (Antunes et al., 2021). The production of concrete using cement poses significant environmental challenges, as it not only depletes substantial natural resources and contributes to construction and demolition waste but also annually releases around 4.1 billion tons of CO_2, constituting nearly 8% of global CO_2 emissions (Nehdi et al., 2004). Furthermore, there is substantial evidence that a long-term bidirectional causal relationship exists between population growth and the

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expansion of the construction industry (Li et al., 2020). According to the U.S. Census Bureau International Database, the projected global population is expected to reach 9 billion by 2037 (Worldometer, 2025) and consequently, there will be a greater demand for construction materials such as concrete and cement in the future. Thus, the concrete industry in general, and production of concrete, in particular, require holistic approaches to decrease their contribution to the global pollutions. In response, there has been extensive research efforts on advancing cement and concrete production technologies to foster decarbonization of the industry (Dobiszewska et al., 2023). Among different decarbonization approaches, a notable one is the adoption of blended cements which incorporate significant quantities of supplementary cementitious material to meet the rising demand for concrete without causing a substantial increase in the production of Portland cement, thereby alleviating the industry's CO_2 footprint. Also, adoption of blended cements becomes an environmentally effective way of reducing proliferation of by-products like fly ash and metallic slag (Zhang et al., 2013; Snellings, 2016). Additionally, it is economically viable, as the supply of these supplementary cementitious materials is abundant in many countries (Nehdi et al., 2004). Therefore, it is anticipated that reducing reliance on the cement in the concrete production could bring significant reductions in overall pollution.

Due to its versatility and cost-effectiveness, plastics have gained popularity across diverse industries such as packaging, automotive, electronics, medical, agriculture, textiles, and even energy (Rossi et al., 2020; Parashar and Hait, 2021; Baldassarre et al., 2022; Jacobsen et al., 2022). The widespread adoption of plastics in different industries also causes significant challenges to marine life, human health, wildlife, natural ecosystems, to name a few (Thompson et al., 2009). From the environmental viewpoint, studies show that out of the 6.3 billion tons of fossil fuel-derived plastic (FFP) waste generated to date, only 9% has been recycled properly while the majority is either incinerated (12%) or improperly disposed of into the environment (79%) (Forrest et al., 2019). FFPs exhibit an extended degradation period, taking centuries to break down, and thus, five billion tons of fragmented and hazardous plastics have been accumulated in our oceans, soil, and air. Without effective recycling strategies, the detrimental impact of FFP waste will deteriorate, posing greater threats to all facets of human life and the environment (Forrest et al., 2019). Reports from the Organization for Economic Co-operation and Development (OECD) indicate that plastics production contributes to approximately 3.5% of global CO_2 pollutions. By considering environmental impacts of plastics, several industries (such as the shoes, sport equipment, and packaging industries) have started adopting a circular economy to recycle and reuse plastics. Such integration could also decrease the weight and improve the quality of a product (Hamada et al., 2024). The use of recycled plastics in the concrete production is promising and could potentially reduce global CO_2 emissions by 15% resulting from the concrete and plastic industries (Adesina, 2020). Although some research studies have examined the use of plastics in the concrete production, there is a lack of comprehensive assessments that consider the full range of impacts throughout its life cycle. Besides, other than environmental plausibility, such an application for plastics should be economically viable in order to take place in practice.

Environmental, social, and governance (ESG) refers to a set of standards employed to measure the broader performance of organizations with regard to the environment and society, well beyond their financial performance (Li et al., 2021). Historically used as a guidance in the context of investing, ESG principles are recently used to improve the performance of supply chains (Dai and Tang, 2022). More specifically, by embracing ESG principles, the concrete industry can adopt more sustainable practices, such as recycling waste plastics to be used in the concrete production. This approach reduces the need for virgin raw materials in the production of concrete, diverts plastics from landfills, and reduces their negative environmental impacts. Economically, it can cut expenses related to the purchase of raw materials and the management of trash (Saha et al., 2023). Socially, ESG-focused practices promote positive stakeholder relations by showcasing a commitment to sustainable development and enhancing community health by cutting back on pollutants (Steiner et al., 2022). Thus, in these highly impactful and resource sensitive industries, a strong involvement of ESG is necessary to promote innovations that reduce environmental impact while boosting economic viability and social welfare (Sanal, 2020). Despite the outmost prominence of concrete production in the construction industry, most research efforts are primarily focused on the environmental and technological aspects of concrete production, failing to examine equally important social and governance aspects.

The ultimate goal of this research is to promote sustainability in the construction supply chains by investigating the role that ESG principles can play. More specifically, this research explores how using treated plastics, integrated into the concrete production, can lead to more sustainable construction practices compared to the traditional ones. A key contribution of the research is simultaneously addressing challenges of reducing CO_2 emissions in both the concrete and plastic industries. In particular, tackling this problem through the lens of ESG is crucial to ensure the applicability of the proposed solutions and their long-term uptake in the industry. The proposed framework in this paper offers a multi-faceted research agenda, combining life cycle assessment (LCA), location-allocation problems (LAPs), and evolutionary game theory (EGT), to evaluate the sustainability of incorporating treated plastics into the concrete production. Another contribution of the paper is investigating the role of major stakeholders of the concrete supply chain into the proposed approach to ensure the developed solutions will satisfy their requirements. The paper integrates both theoretical modeling and empirical analysis, based on a case study in Halifax Regional Municipality (HRM), Canada.

The rest of the paper is presented in five sections. Section 2 reviews the relevant literature. Section 3 defines the problem and describes the proposed approach to address the problem. In Section 4, the numerical analyses are performed to validate the proposed approach and presented together with the managerial insights. Finally, conclusions and future directions are described in Section 5.

2. Literature review

This section reviews the relevant literature across five subsections. First, it examines existing research on the use of waste plastics in the construction industry. Second, it explores studies that integrate LCA with the application of waste materials in construction.

Third, the related literature on LAPs is analyzed. Fourth, it investigates the use of game theory in the context of the construction sector. Finally, the section identifies key research gaps emerging from these thematic areas.

2.1. Concrete and recycled plastics

Recent research has increasingly explored the incorporation of treated plastic waste into concrete, offering valuable insights not only into material performance but also into strategic sustainability planning within the construction industry. Hamada et al. (2024) reviewed studies from 2020 to 2024 and emphasized that using treated plastic waste, particularly polyethylene terephthalate (PET) and polypropylene (PP), as aggregate can reduce concrete density and reliance on raw materials while maintaining acceptable mechanical performance for many non-structural applications. Their findings suggest that plastic-modified concrete could be systematically deployed in applications such as paving blocks, partitions, and low-load infrastructure to reduce material costs and environmental impact, especially in regions experiencing aggregate shortages. Experimental work by Sau et al. (2024) further demonstrated the durability advantages of incorporating recycled polyethylene (PE) and PET in varying volumetric proportions, reporting improved impact resistance and reduced chloride penetration under aggressive environmental conditions. From a construction management standpoint, their study supports the targeted use of treated plastics in coastal and wastewater-related projects, where chemical durability is a critical requirement. Importantly, their findings indicate that environmental performance can be enhanced without compromising service life, aligning with life cycle cost-reduction strategies in public infrastructure development. In a broader context, Haba et al. (2025) investigated the use of plastic waste as both filler and binder in composite materials, highlighting key differences between thermoplastics and thermosets in terms of rigidity, water absorption, and bonding quality. Their review underscores that plastic waste is not a one-size-fits-all solution; rather, its selection should be tailored to performance objectives (e.g., thermal insulation vs. mechanical load-bearing capacity). For decision-makers in sustainability planning, the study advocates for the integration of waste management policies with construction specifications, promoting a circular economy model in which plastic waste streams are pre-sorted and allocated to suitable concrete applications. Duraiswamy et al. (2024) advanced this perspective by combining plastic fibers with treated construction and demolition waste (CDW), achieving improvements in tensile and flexural strength while confirming minimal fiber degradation through SEM/EDS analysis. Their managerial contribution lies in demonstrating a dual-benefit strategy: diverting plastic from landfills while simultaneously valorizing CDW. This approach enables local governments and construction firms to meet waste reduction targets and reduce dependence on virgin aggregates. Their findings suggest the potential for public-private partnerships designed to recover, treat, and standardize plastic fibers and CDW for use in municipal concrete works. Mashaan (2024) offered a comprehensive synthesis of performance evaluations involving various plastic types-including HDPE, LDPE, PVC, and PET-and stressed the importance of customizing mix designs to match each plastic's mechanical characteristics. Beyond technical assessments, the study calls for further research into long-term durability and environmental trade-offs, urging construction engineers and policymakers to expand performance-based specifications to include sustainability metrics when integrating recycled plastics into large-scale infrastructure projects. Last but not least, Asif et al. (2024) proposed a machine learning framework using multi-expression programming to predict compressive and tensile strength in plastic-based concrete with high accuracy. Their sensitivity analysis revealed that both cement and plastic content significantly influence strength outcomes, providing project engineers with a practical tool to rapidly evaluate design scenarios without relying solely on costly experimental procedures. From a managerial perspective, this enables more informed decision-making during the design phase, reducing waste and enhancing predictive control over material behavior-both essential elements in lean construction and green building certification initiatives.

2.2. Life cycle assessment

Attaining sustainable development goals requires robust and comprehensive tools to holistically evaluate sustainable solutions. LCA provides a systematic approach to account for the environmental impacts of materials and processes across their full life cycle, supporting informed decision-making in sustainable development initiatives (Hauschild et al., 2018).

The application of LCA in the construction industry is well-established. Early studies predominantly focused on traditional materials, such as cement and aggregates. For example, Manjunatha et al. (2021) assessed the environmental impacts of ordinary Portland cement (OPC), ground granulated blast furnace slag (GGBFS), and Portland pozzolana cement (PPC), finding OPC to have lower impacts in their case. Similarly, Marinković et al. (2010) compared LCA outcomes of recycled aggregate concrete with natural aggregate concrete, incorporating local data to enhance contextual accuracy. Chen et al. (2010) evaluated the influence of supplementary cementitious materials such as blast furnace slag and fly ash, highlighting the importance of policy decisions in shaping recycling outcomes. Butera et al. (2015) extended the scope of LCA to the end-of-life phase, emphasizing that emissions from leaching within the use phase could exceed those from production, underlining the importance of a full life cycle perspective.

More recent studies have expanded LCA applications to the integration of plastic waste in construction materials. Ibrahim et al. (2024) conducted a comparative LCA and life cycle cost analysis (LCCA) on hot-mix asphalt incorporating devulcanized rubber (DVR) and low-density polyethylene (LDPE), demonstrating a 54.5% reduction in greenhouse gas emissions alongside cost savings. Sharma et al. (2024) employed LCA to assess recycled materials in Indian road construction, including plastic-containing waste, confirming significant reductions in environmental burdens tied to landfill diversion and raw material conservation. Zakerhosseini et al. (2024) applied LCA to construction and demolition waste (CDW) management in Iran, incorporating human toxicity indicators and underscoring the value of recycling-including plastics-in sustainable demolition practices.Broader LCA syntheses have also highlighted the potential of plastics in construction. Marson et al. (2023) systematically reviewed 79 comparative LCA studies on plastics, noting that recycled plastic products often outperform virgin plastics and some alternative materials in environmental performance, particularly when end-of-life impacts are considered. Qiao et al. (2022) supported these findings through dedicated LCA analyses of recycled construction products such as bricks and insulation blocks containing CDW plastics. Complementing this, Jain et al. (2020) demonstrated the superiority of integrated recycling systems, which commonly process plastic fractions, over inert landfilling in Indian urban environments. Overall, the literature shows a growing emphasis on the environmental benefits of integrating recycled plastics into construction applications. However, methodological variations and data limitations, as highlighted by Marson et al. (2023), suggest the need for harmonized LCA practices, especially when evaluating emerging treatment technologies such as chemical functionalization.

2.3. Location-allocation problem

Location-allocation problems (LAPs) are a class of optimization models that play a crucial role in various fields, including logistics, urban planning, and facility management (Saldanha-da Gama, 2022). These problems aim to determine the optimal placement of facilities, (such as warehouses and service centers) to efficiently serve the demands of a given region (Liu et al., 2022). The common objectives of LAPs are to minimize costs, maximize service coverage, or achieve a balance between these two objectives. LAPs involve complex spatial considerations, including distances, travel times, and resource constraints, making them critical for decision-makers seeking to enhance resource utilization and service accessibility (Zhang et al., 2016; Sun and Zhang, 2020). Through mathematical modeling and algorithmic approaches, LAPs offer valuable insights into optimizing infrastructure deployment and resource allocation in diverse real-world contexts (Lin, 2014; Purkayastha et al., 2015).

Within the context of the construction industry, LAPs has always been popular. Cheng et al. (2021) addressed the facility location problem under demand uncertainty situation for construction sectors. They developed a two-stage robust mathematical model and used column-and-constraint generation (C&CG) algorithm for solving the model. In a related study, Güden and Süral (2014) applied the LAP to a railway construction project where they used the LAP model to determine the optimal locations, quantities, and types of mobile concrete batching facilities. In order to choose the optimal placement for a collection station, Badran and El-Haggar (2006) presented a mixed-integer programming model, with the primary goal of minimizing the overall costs of running the municipal solid waste system. The overall costs consists of the fixed cost of constructing facilities and the cost associated with the operations and transportation networks. In another study, Erkut et al. (2008) utilized a mixed-integer multi-objective linear programming model to address the LAP of municipal solid waste facilities in the Central Macedonia region of Northern Greece. Toso and Alem (2014) addressed the issue of sorting center placement in a medium-sized Brazilian city. The researchers provided a risk-averse model, a two-stage recourse formulation, and a traditional deterministic capacitated facility location problem. In addressing the complex issue of waste facility siting in urban developing areas, a study by Sambiani et al. (2023) proposed a framework for siting waste to energy facilities and transfer stations using a multi-criteria decision analysis approach. This framework makes use of location-allocation techniques, a fuzzy analytical hierarchy process, and geographic information systems (GIS).

2.4. Game theory in sustainable supply chain

Game theory is a branch of mathematics and economics that explores strategic interactions between rational decision-makers (Xiao et al., 2023). It provides a powerful framework for analyzing and understanding how individuals, businesses, or nations make decisions when their decision outcomes depend on the choices of others. Games can range from simple scenarios like pricing competition between two companies to complex geopolitical negotiations (Marwala, 2023; Rajabzadeh et al., 2023; Deng et al., 2024). Central to game theory are concepts like Nash equilibria (NE), which represent stable outcomes where no player can improve their position by unilaterally changing their strategy. Within the context of supply chain management, game theory is widely used, particularly to determine optimal pricing strategies for its members, including manufacturers and retailers. Gao et al. (2018) examined a Stackelberg game involving the government and manufacturers as key stakeholders with the objective of identifying optimal solutions for tax rates, the level of environmental sustainability, and product pricing. The study derived strategies for both the government and manufacturers across various environmental policy scenarios. Jabarzare and Rasti-Barzoki (2020) examined a dual-channel supply chain comprising a manufacturer and a packaging company. In addition to analyzing product pricing, they investigated product quality in various scenarios and found that if the primary objective is to enhance the product quality, cooperation between the packaging company and the manufacturer can yield greater benefits for both parties. In another study, Parsaeifar et al. (2019) examined a multi-echelon supply chain, which included a single producer alongside multiple retailers and suppliers. The study focused on the competition among retailers and suppliers to determine the optimal pricing strategy and the degree of product greenness and the results indicate that the profitability of retailers increases as the level of market competition among them increases. Li et al. (2016) investigated the pricing policies within a supply chain subject to government interventions. They considered a dual-channel green supply chain context, comprising a manufacturer and a retailer when customer preferences were included into their mathematical model. They found that subsidies enhance the sustainability of products and lead to increased profits for manufacturers. Additionally, a stronger preference for green products by consumers results in a higher demand for sustainable products. Similarly, Ranjan and Jha (2019) conducted a study on a dual-channel green supply chain to determine the optimal pricing strategy and greening degree of the products in both direct and indirect channels. In their proposed model, the direct channel dealt with green products, while the indirect channel handled non-green products. The model was analyzed in three distinct scenarios: centralized, decentralized, and collaborative. The results indicate that the collaboration model, in particular, achieved a high level of quality for the green product. Zhang et al. (2023) employed game theory for the solar energy supply chain context, specifically focusing on a closed-loop system for solar photovoltaic recycling to determine the pricing levels and investments in each channel of the supply chain. Furthermore, they analyzed how cost parameters affected government-implemented systems and optimal decision-making. The findings suggest that in cases of low-cost investments, subsidies prove to be more efficient than penalties. Conversely, for high-cost investments, both policy approaches have positive effects on the formal treatment rate of waste photovoltaic modules.

2.5. Research gaps

Recent research on the use of waste plastics in concrete and construction supply chains has made important progress, but it has largely evolved along separate and weakly connected streams. On the environmental side, several studies employ LCA to quantify emissions and environmental benefits of plastic-modified concrete mixes, providing valuable insights at the material level, yet without considering the logistics and infrastructure required for large-scale deployment (Rispoli and Ajibade, 2024; Ahmed and Abdulqudos, 2024). In parallel, supply-chain and network design models in the construction and waste-management sectors focus on facility location, capacity planning, and cost-emission trade-offs, but typically treat environmental parameters as static inputs and abstract from specific end-use applications such as green concrete (Jebreili et al., 2025; Brandão et al., 2021). A third body of work emphasizes governance and stakeholder dimensions-examining policy instruments, institutional arrangements, or social barriers affecting circular construction practices-but these studies are often qualitative or descriptive and do not feed stakeholder behavior back into formal optimization or network design models (Adabre et al., 2023; Barford and Ahmad, 2024). As a result, existing approaches tend to examine environmental, economic, or governance dimensions in isolation. Therefore, based on the reviewed literature, the following research gaps are identified.

- Although prior studies have examined alternative materials in concrete production and assessed their life cycle impacts, the integration of post-consumer waste plastics into concrete supply chains has rarely been evaluated in a manner that links material-level environmental performance to system-level implementation.
- The environmental impacts associated with chemical treatments used to process waste plastics have not been comprehensively assessed. These treatments, applied at different stages to prepare plastics for reuse, may introduce additional environmental burdens that are often omitted from conventional assessments.
- Location-allocation models in waste management and construction logistics have primarily focused on minimizing cost or emissions independently, with limited attention to jointly optimizing cost and pollution while explicitly accounting for treatment capacity decisions at waste treatment centers.
- While several studies address the environmental benefits of plastic use in construction, there remains limited understanding of how public awareness and policy-driven demand shifts influence market adoption and pricing behavior among concrete producers.
- Much of the existing economic literature relies on static or classic game-theoretic approaches to analyze competitive behavior in the construction industry. However, the transition toward reduced cement use and low-carbon concrete is inherently dynamic, requiring models that can capture temporal evolution in producer adoption and market shares.
- Despite the central role of government as a regulator and policy-maker, its influence on the decarbonization of concrete production-and its interaction with supply-chain members' strategic behavior-remains underexplored in existing modeling frameworks.

To address the above gaps, this study makes four main contributions. First, an ESG-oriented analytical framework was developed that simultaneously accounts for environmental impacts (via LCA), economic performance (through cost and pricing models), and governance policies (through government interventions and awareness mechanisms). Second, three methodological components (i.e., LCA, bi-objective location-allocation modeling and EGT) were integrated to capture both operational decisions and dynamic strategic interactions along the recycled concrete supply chain; to the best of our knowledge, such a combination has not been examined in prior research. Third, the behavioural evolution of green and non-green concrete producers under different government policy scenarios was explicitly modeled, providing new insights into adoption pathways and technology diffusion in sustainable construction. Finally, the practical implications of the proposed framework were validated through a Canadian case study, demonstrating how ESG considerations can reshape supply chain configurations and support evidence-based policy decisions.

3. Methodology

3.1. Problem description

This research examines how the environmental impact of the concrete industry can be reduced by partially replacing cement with chemically treated post-consumer plastics, as suggested in the literature. Prior studies indicate that incorporating plastics into concrete may also enhance certain mechanical and physical properties (Belmokaddem et al., 2020; Awoyera et al., 2021). Fig. 1 illustrates the role of plastics in the concrete production process and highlights the key raw materials involved in cement and concrete manufacturing.

This study considers a multi-tier supply chain designed to efficiently integrate treated plastics into concrete production. As shown in Fig. 2, the supply chain consists of three levels. At the first level, landfills and manufacturers generating large volumes of plastic waste supply used plastics for further processing. At the second level, cement producers and waste treatment centers (WTCs) operate jointly: WTCs perform the chemical treatment that converts plastic waste into suitable cementitious inputs, while cement producers supply the binding material required for concrete production. The third level comprises concrete plants, which combine treated plastic and cement to produce environmentally conscious concrete products.

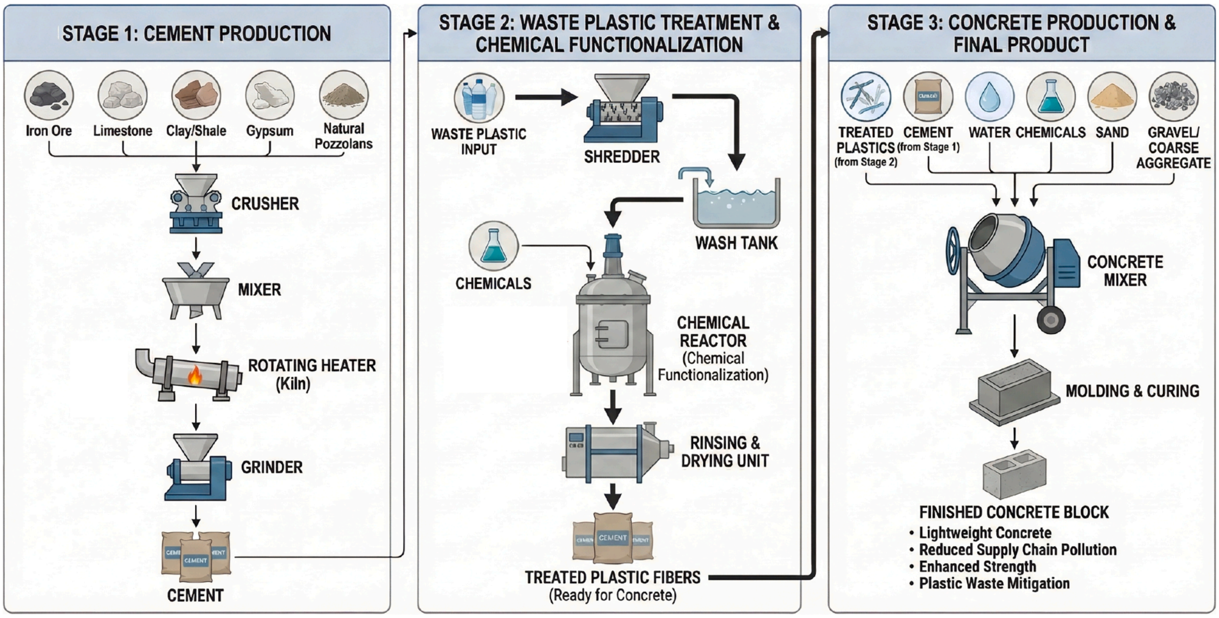


Fig. 1. The schematic view of the analyzed concrete production method.

Within this multi-tier system, a key challenge arises in determining the optimal locations and capacities of WTCs. Strategic placement of these centers is essential to minimize transportation costs, improve resource utilization, and ensure a reliable flow of materials throughout the supply chain. Capacity decisions further influence feasible plastic-to-concrete conversion ratios and the ability to meet demand for sustainable construction materials. Accordingly, the primary objective of this study is to formulate and solve an optimization problem that identifies appropriate WTC locations and capacity levels while minimizing the environmental impacts of the overall concrete supply chain.

Before presenting the mathematical models, it is necessary to assess both the environmental implications of the plastic treatment process and the economic incentives faced by concrete producers. Environmental performance is evaluated using a LCA that compares treated-plastic concrete with conventional concrete. Producer incentives are examined through an evolutionary game-theoretic (EGT) framework that determines equilibrium prices and predicts how producers transition from conventional to treated-plastic-based production. These strategic decisions are influenced by governance mechanisms such as taxes, subsidies, and awareness initiatives, which play an important role in shaping adoption patterns across the industry.

Government support for low-carbon construction materials is well established in current policy practice. In Canada, federal programs such as the Investing in Canada Infrastructure Program's Green Infrastructure Stream, the emerging Buy Clean strategy, and the Canada Green Buildings Strategy explicitly promote the use of low-embodied-carbon materials, including concrete mixes incorporating recycled inputs (Infrastructure and Canada, 2025; Hasanbeigi et al., 2022; Canada, 2025). At the provincial level, initiatives such as CleanBC similarly encourage lower-carbon concrete formulations and greater use of recycled aggregates (Sutton, 2024). Comparable efforts exist internationally. In the United States and European Union, federal funding mechanisms and green public-procurement requirements are increasingly used to support low-emission cement, recycled plastic inputs, and other low-carbon construction materials (Force, 2025; Bellona, 2025). These examples demonstrate that subsidies, procurement incentives, and related policy instruments represent realistic and widely adopted tools for supporting sustainable concrete technologies.

Moreover, a set of key assumptions considered in this study is outlined below.

1. Demand functions for concrete producers are assumed to follow a linear form (Yan et al., 2011; Hafezalkotob et al., 2018).
2. To ensure non-negative demand values, the market's base demand is assumed to be sufficiently large relative to other model parameters (Swami and Shah, 2013).
3. In each distribution channel, self-price elasticity exceeds cross-price elasticity, meaning demand is more sensitive to a producer's own price than to competitors' prices ($\rho > \sigma > 0$) (Mahmoudi et al., 2022).
4. The self-price elasticity of each concrete producer exceeds the sensitivity of demand to public awareness ($\rho > \lambda > 0$) (Li et al., 2016).
5. Cement producers are assumed to have sufficient capacity to meet the demand of concrete producers.
6. Concrete producers are able to adjust their production capacity in response to market demand.

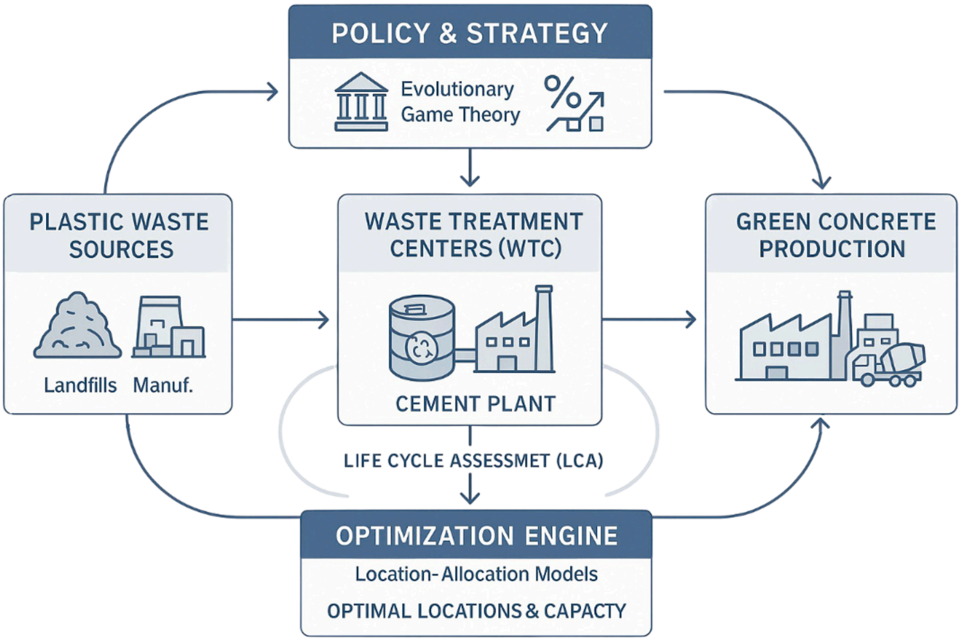


Fig. 2. The scheme of the defined problem for the sustainable concrete supply chains.

3.2. Proposed framework

Fig. 3 presents the proposed framework that addresses the core components of the problem. The first step involves employing a LCA to evaluate the long-term environmental and human health impacts of the plastic treatment process. LCA plays a critical role in validating the sustainability of integrating treated plastics into the concrete production process.

The second step introduces a bi-objective mathematical model (Model 1) designed to minimize total pollution and cost across the entire concrete supply chain. This supply chain includes plastic waste suppliers (i.e., landfills and manufacturers), waste treatment centers (WTCs), cement plants, and concrete producers. The primary goal of this model is to determine the optimal location and capacity of the WTCs.

The third step develops an EGT model to capture strategic interactions among concrete producers. This model provides a powerful tool for identifying optimal decision-making strategies within the supply chain. By simulating behavioral dynamics through EGT, the study identifies optimal pricing, quantities, and profits. At this stage, concrete producers choose between two strategies: a “green” strategy, which incorporates treated plastics, and a “non-green” strategy based on conventional production methods. The framework also accounts for potential government influence on decision-making, whether direct or indirect, reflecting real-world policy environments.

In the final step, the insights gained from the previous stages are incorporated into a second location-allocation model (Model 2), which focuses on maximizing the profitability of concrete producers who adopt green practices. Based on the outcomes of the EGT model, the new model identifies the location and capacity of these green producers to ensure long-term economic viability.

The proposed framework offers a structured approach to address all three pillars of ESG (environmental, social, and governance) in a concrete supply chain context. Specifically, the environmental aspect is addressed in the first step, while the second through fourth steps incorporate both social and governance perspectives, alongside economic considerations.

The methodological sequence adopted in this study reflects the multi-layer structure of the research objectives. The LCA provides the foundational environmental comparison between traditional concrete and mixes incorporating treated plastic. Building on these results, Model 1 evaluates cost-emission trade-offs in locating and sizing waste treatment centers across the supply chain. The evolutionary game model then examines how concrete producers adjust their pricing and adoption decisions in response to policy instruments such as subsidies, taxes, and awareness initiatives. Finally, Model 2 incorporates the resulting adoption patterns and market shares to assess the broader operational and economic implications of ESG-oriented policies. Together, these elements form an integrated decision-making framework that links environmental assessment, operational design, and strategic behaviour. This structure also aligns with the ESG lens of the study: LCA addresses the environmental dimension, the optimization and pricing components capture the economic dimension, and the policy mechanisms embedded in the evolutionary game model represent the governance dimension.

The following subsections elaborate on each step of the framework in detail.

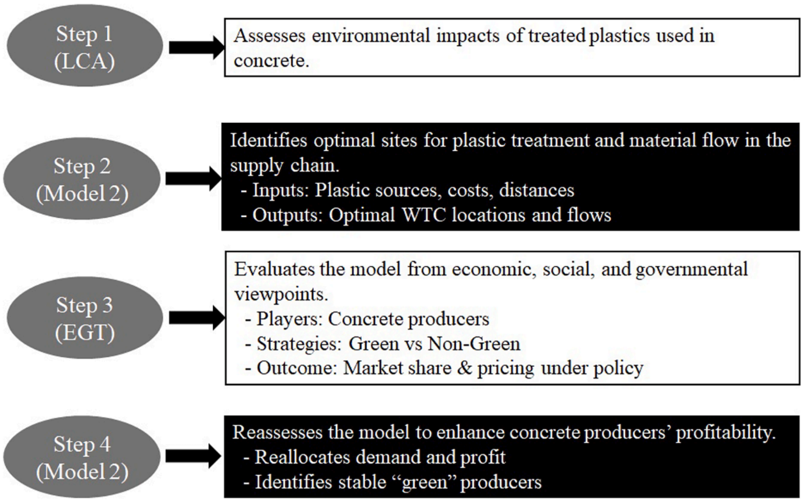


Fig. 3. Proposed research framework.

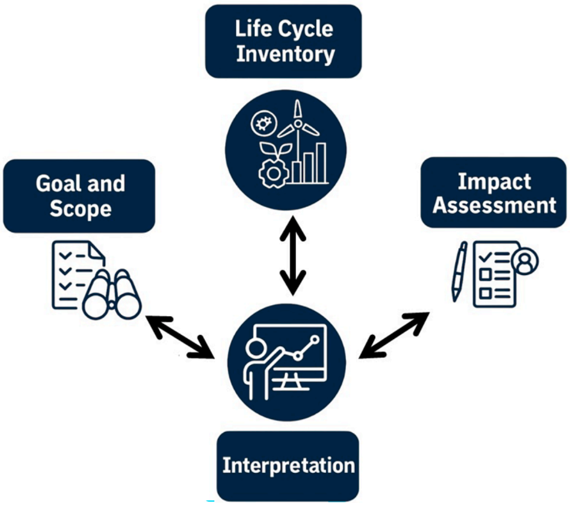


Fig. 4. An overview of the LCA structure.

3.2.1. *Life cycle assessment*

LCA is an environmental management tool used to evaluate the environmental impacts and burdens associated with a product or service (Pourahmadiyan et al., 2021). The assessment initiates with quantifying the utilization of materials and energy, as well as the release of waste throughout its entire life cycle. Although initial focus of LCA is on environmental aspects and often overlooks economic and social impacts, its comprehensive life cycle approach can be extended to encompass other objectives as well (Xing et al., 2022). The prevailing standards governing the LCA approach are ISO 14040: 2006 and ISO 14044: 2006. Fig. 4 provides an overview of the LCA methodology (Manjunatha et al., 2021).

The initial stage in LCA involves defining the goal and scope of the assessment. This encompasses identifying the boundaries of the system under analysis and establishing specific environmental aspects to be considered. Subsequently, the life cycle inventory (LCI) stage focuses on compiling a comprehensive inventory of inputs and outputs throughout the entire life cycle, encompassing materials, energy, emissions, and waste. Following the LCI, the Life Cycle Impact Assessment (LCIA) evaluates potential environmental impacts identified in the inventory, using established categories such as global warming, ozone depletion, acidification, and eutrophication. At the end, the Interpretation stage then involves a critical analysis of LCA results, considering uncertainties and limitations, and drawing insightful conclusions for decision-making. This sequential process provides a holistic understanding of the environmental implications associated with a product or process, offering valuable insights for sustainable decision-making (Saade et al., 2020; Sauve and Van Acker, 2020; Thonemann et al., 2020). This research employs SimaPro software (SimaPro, 2024) for LCA. Fig. 5 illustrates the conceptual flowchart of the treatment procedure used for preparing the recycled plastics, based on previously validated laboratory protocols.

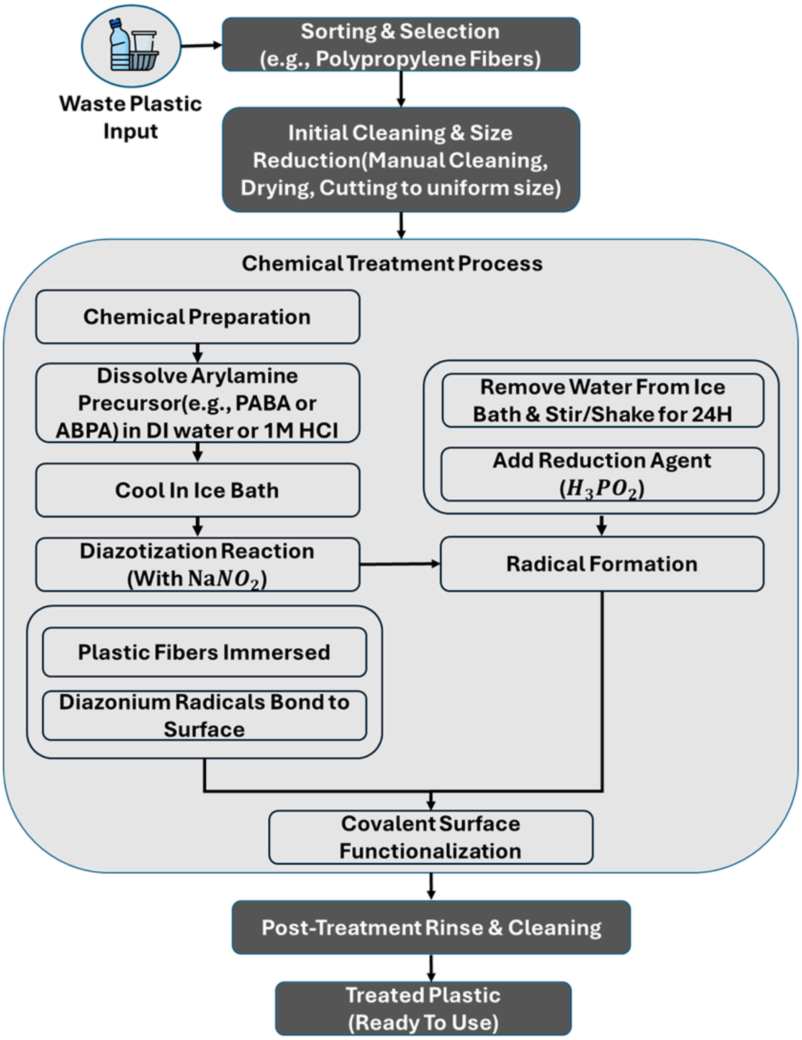


Fig. 5. Conceptual flow diagram of the plastic treatment process used as the basis for LCA modeling.

As shown by Fig. 5, in this study, the plastic treatment process, modeled within the LCA, is based on a chemical surface functionalization approach, adapted from experimentally validated protocols involving diazonium reactions. This method involves the covalent bonding of functional groups to recycled PET through reactions with sodium nitrite, arylamines, and hypophosphorous acid in an acidic medium. While minimal pre-treatment steps are assumed (e.g., cleaning and size reduction), the primary treatment is classified as a chemical modification process rather than mechanical or thermal transformation.

It is important to clarify that the focus of this study is specifically on chemically treated PET. However, the proposed framework remains flexible and could be extended to accommodate other plastic types and treatment approaches. For example, thermoplastics such as PE and polyvinyl alcohol (PVA), commonly found in packaging, are often subjected to mechanical treatments such as shredding or grinding prior to use in construction materials (Uzosike et al., 2023; Schyns and Shaver, 2021). In contrast, thermoset plastics, including epoxy resins used in coatings and adhesives, typically require more intensive chemical or thermal recycling methods, such as pyrolysis (Türel et al., 2023; Klose et al., 2023). Although this study models a single chemical treatment process applied to PET, the modular structure of the LCA and optimization models allows for adaptation to other treatment pathways, supporting broader applicability in sustainable concrete applications

3.2.2. Location-allocation model (model 1)

This subsection elaborated on the first mathematical model for the LAP. A summary of the model notations is presented in Table 1.

This paper focuses on two key areas: the economic feasibility and the environmental impact of the concrete supply chains. In the first location-allocation model, the economic feasibility entails the study of the supply chain costs, including transportation expenses and various costs associated with the recycling units. Costs further include the expenses for recycling processes, day-to-day operations, and setting up and establishment of the recycling facility. The first objective function is represented by Eq. (1). By involving α_g, the

Table 1
List of sets, variables, and parameters.

Notation	Description
Sets	
G	Set of plastic resources, indexed by $g \in G : \{1, 2, \dots, n, n+1, \dots, \lvert G \rvert\}$
M	Set of waste treatment centers, indexed by $m \in M : \{1, 2, \dots, \lvert M \rvert\}$
T	Set of cement plants, indexed by $t \in T : \{1, 2, \dots, \lvert T \rvert\}$
J	Set of concrete plants, indexed by $j \in J : \{1, 2, \dots, \lvert J \rvert\}$
Parameters	
ζ^L_{gm}	Transportation cost of plastic from plastic resource g to waste treatment center m (\$/ton.km)
ζ^C_{tj}	Transportation cost of cement from cement plant t to concrete plant j (\$/ton.km)
ζ^R_{mj}	Transportation cost of treated plastic from waste treatment center m to concrete plant j (\$/ton.km)
ω^f_m	Fixed cost for establishing waste treatment center m (\$)
ω^r_m	Recycling cost in waste treatment center m (\$/ton)
ω^o_m	Operational cost (warehousing, separation, cleaning, etc.) (\$/ton)
α_g	Plastic contamination level from plastic supplier g ($\alpha_g \geq 1$)
ξ^L_{gm}	Transportation emissions of plastics from plastic resource g to waste treatment center m (CO_2/ton.km)
ξ^C_{tj}	Transportation emissions of cement from cement plant t to concrete plant j (CO_2/ton.km)
ξ^R_{mj}	Transportation emissions of plastic from waste treatment center m to concrete plant j (CO_2/ton.km)
e^L_m	Treating process emissions at waste treatment center m (CO_2/ton)
e^C_t	Production emissions of cement at cement plant t (CO_2/ton)
e^T_j	Production emissions of concrete at concrete plant j (CO_2/ton)
D_j	Market demand for concrete from concrete plant j (ton)
β	Ratio of cement to treated plastic per unit (%)
d^L_{gm}	Distance between plastic resource g and waste treatment center m (km)
d^R_{mj}	Distance between waste treatment center m and concrete plant j (km)
d^C_{tj}	Distance between cement plant t and concrete plant j (km)
C^L_g	Capacity of plastic resource g (ton)
C^T_t	Capacity of cement plant t (ton)
TC	Capacity of trucks (ton)
Variables	
x^C_{tj}	Amount of cement purchased by concrete producer j from cement producer t (ton)
x^R_{mj}	Amount of treated plastic purchased by concrete producer j from waste treatment center m (ton)
x^L_{gm}	Amount of wasted plastic collected by waste treatment center m from plastic supplier g (ton)
δ_m	Capacity of waste treatment center m (ton)

proposed model enables us to investigate the role recent advancement in integration of plastic into concrete. In other words, α_g helps distinguish variations among plastics types in this context. In certain cases, additional cleansing agents may be required to enhance the purity of a specific fraction of the plastic materials.

$$\begin{aligned}\min Z_1 = &\left(\sum_{g=1}^{G}\sum_{m=1}^{M} y^L_{gm}\omega^f_m + \sum_{g=1}^{G}\sum_{m=1}^{M} x^L_{gm}\alpha_g\left(\omega^R_m + \omega^O_m\right)\right)\\ &+\left(\sum_{g=1}^{G}\sum_{m=1}^{M} x^L_{gm}\zeta^L_{gm}d^L_{gm} + \sum_{j=1}^{J}\sum_{t=1}^{T} x^C_{tj}\zeta^C_{tj}d^C_{tj} + \sum_{m=1}^{M}\sum_{j=1}^{J} x^R_{mj}\zeta^R_{mj}d^R_{mj}\right)\end{aligned} \tag{1}$$

$$\begin{aligned}\min Z_2 = &\left(\sum_{g=1}^{G}\sum_{m=1}^{M} x^L_{gm}\xi^L_{gm}d^L_{gm} + \sum_{j=1}^{J}\sum_{t=1}^{T} x^C_{tj}\xi^C_{tj}d^C_{tj} + \sum_{m=1}^{M}\sum_{j=1}^{J} x^R_{mj}\xi^R_{mj}d^R_{mj}\right)\\ &+\left(\sum_{g=1}^{G}\sum_{m=1}^{M} x^L_{gm}\alpha_g e^L_m + \sum_{j=1}^{J}\sum_{t=1}^{T} x^C_{tj}e^C_t + \sum_{j=1}^{J} e^T_j D_j\right)\end{aligned} \tag{2}$$

$s.t.$:

$$\sum_{m=1}^{|M|} x^L_{gm} \leq C^L_g, \quad \forall g \in G \tag{3}$$

$$\sum_{j=1}^{|J|} x^R_{mj} \leq \varepsilon \sum_{g=1}^{G} x_{gm}, \quad \forall m \in M \tag{4}$$

$$\sum_{g=1}^{|G|} x^L_{gm} \leq \delta_m, \quad \forall m \in M \tag{5}$$

$$\sum_{t=1}^{|T|} x^C_{tj} \geq \beta^C D_j, \quad \forall j \in J \tag{6}$$

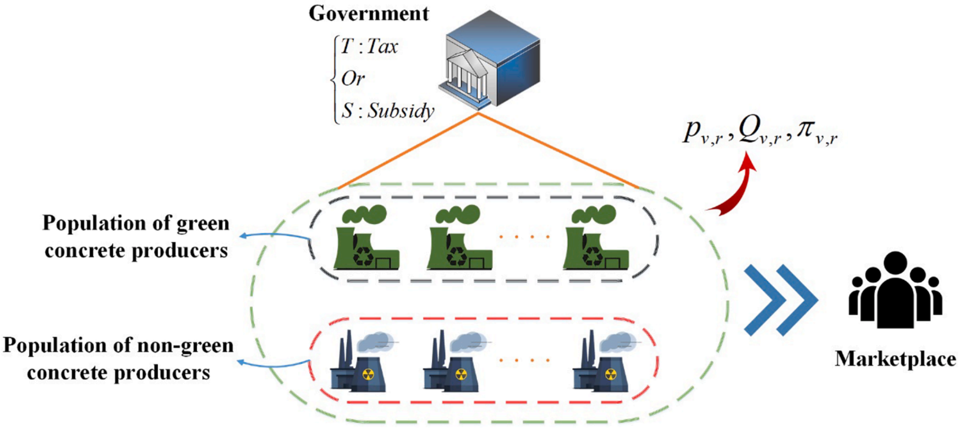


Fig. 6. General schema of the proposed game-theory model.

$$\sum_{m=1}^{|M|} x_{mj}^{R} \geq \beta^{R} D_{j}, \quad \forall j \in J \tag{7}$$

$$x_{gm}^{L} \leq M y_{gm}^{L}, \quad \forall g \in G, \forall m \in M \tag{8}$$

$$y_{gm}^{L} \in \{0,1\} \tag{9}$$

$$x_{tj}^{C}, x_{mj}^{R}, x_{gm}^{L}, \delta_{m} \geq 0 \tag{10}$$

The first objective function (Z_1) minimizes the total cost of the supply chain. The first term in Eq. (1) refers to the expenses related to the recycling unit, while the subsequent term addresses the transportation costs. The second objective function considers the pollution generated during transportation and production processes in Eq. (2). The first term computes the extent of transportation-related pollution throughout the entire supply chain. The second term delineates the emissions generated during the plastic treatment process, and pollutions related to production in cement and concrete plants, respectively.

The constraints of the model are presented in Eqs. (3)–(8). In accordance with Eq. (3), each supplier has a maximum capacity for transporting plastics to plastic treatment centers. Furthermore, in practical scenarios, there is a possibility of plastic material wastage during the treatment process, meaning that a proportion of plastics will not be usable. Considering this, Eq. (4) indicates that the maximum amount of plastics that can be transported from treatment centers to concrete producers is a specific amount of the input of plastics to that treatment center.

In this study, the plastic treatment centers' capacity is considered as a variable, and its calculation is based on Eq. (5). As previously indicated, concrete producers blend cement and treated plastics to achieve the final concrete mixture. Consequently, they need to procure cement and plastics in specific proportions. To elucidate this correlation, parameters $0 \leq \beta^{c}, \beta^{R} \leq 1$ have been employed in Eqs. (6)–(7). Here, it is assumed that $\beta^{c} = 0.12$ and $\beta^{R} = 0.03$. Moreover, Eq. (8) explains that the variable $x_{g,m}^{L}$ assumes a value contingent upon the activation of the corresponding route.

3.3. Basic game model for concrete producers

Concrete producers have a great role in transitioning to a sustainable construction industry. Therefore, it is essential to ensure involve them in the decision-making process. One of the key drivers in this endeavor is demonstrating the multitude of benefits they can gain from such practices. To satisfy the economic objectives of concrete producers, the concrete selling price becomes a paramount factor. Given the abundance of manufacturers in the market and a diverse customer base, concrete producers should engage in competitive strategies to gain a larger share of the market, ultimately leading to an increased profitability. The literature suggests game theory as one of the best mathematical tools for simulating competition and conflict situations between players in a given market (Zhao et al., 2020; Kumar et al., 2021). Fig. 6 illustrates the developed conceptual game model. The model consists of two distinct sets of players: green concrete producers utilizing treated plastics, and non-green concrete producers using traditional materials. Furthermore, this study considers the pivotal role played by the government in incentivizing concrete producers to adopt environmentally friendly practices, a concept that has been substantiated in the previous research (Mahmoudi and Rasti-Barzoki, 2018; Mahmoudi et al., 2021; Zhang et al., 2024).

It is assumed that the government can encourage producers to transition using treated plastics by offering subsidies. Conversely, non-green producers may face penalties in the form of taxes imposed by the government. Additionally, the government should play a role in enhancing public awareness about the advantages of using green concrete over non-green alternatives. To achieve this, it is assumed that the government will allocate resources for advertising initiatives. The notations used in the game theory model are presentation in Table 2.

Table 2
List of sets, variables, and parameters in the proposed game theory approach.

Notation	Description
Sets	
v, r	Strategies used by different concrete producers (i.e., green and non-green)
Parameters	
ϕ	Market size
ρ	Self-price elasticity in the demand function
σ	Cross-price elasticity of the demand
λ	Coefficient of public awareness in the use of green concrete
$w_{v,r}$	Greening effort level
c	Cost of concrete production
$L_{v,r}$	The reservation profit considered by concrete producers using strategy v relative to the concrete producer employing strategy r
Variables	
$p_{v,r}$	Concrete price for concrete producer using strategy v relative to producer using strategy r (\$/ton)
T	The tax imposed on concrete producer by the government (\$/ton)
S	The subsidy allocated to the concrete producer by the government (\$/ton)
Dependent variables	
$Q_{v,r}$	Demand for concrete producer using strategy v relative to producer using strategy r (ton)
$\pi_{v,r}$	Profit function for concrete producer using strategy v relative to plant using strategy r (\$/ton)
π^{Gov}	The government's profit function (\$/ton)

This section discusses the modeling of demand and profit functions for a population of concrete producers, considering both green and non-green strategies across three distinct scenarios. It is essential to highlight that, due to the symmetric nature of the evolutionary game environment, all calculations and analyses are presented from the perspective of one player, for example, Player 1. The symmetry game theory, expressed as $Y = X^T$, implies that selected individuals can exchange roles without any modifications. This indicates a seamless transition without the need for adjustments. Taking into account the strategies mentioned, we can outline the following strategy profiles for concrete producers.

In the first strategy profile, both concrete producers will employ treated plastics. This study assumes a community inclination towards environmentally friendly options. Consequently, the demand function for the producers, beyond the product price, will be influenced by the proportion of their competitors utilizing treated plastic. Eqs. (11)–(12) represents the demand and profit function. According to assumption 1, demand is considered to be in a linear form, dependent on factors such as market size, product price in various distribution channels, and variables like public awareness. Moreover, the literature (Mahmoudi et al., 2021; Mondal and Giri, 2024) suggests that the green investment of socially concerned producers could be represented in a quadratic form, such as lw^2, where l denotes the cost coefficient associated with the green strategy.

Finally, profit is calculated as the difference between revenue and costs. In this strategy profile, revenue includes the selling price and the subsidy allocated to concrete producers, while both production costs and the additional expenses incurred in transitioning towards greener products are considered as total costs. Taking these factors into account, profit function can be formulated by Eq. (12).

$$Q_{v,r} = \phi - \rho p_{v,r} + \sigma p_{r,v} + \lambda_1 w_{v,r} - \lambda_2 w_{r,v} \quad \forall v, r \in \{\text{green}\} \tag{11}$$

$$\pi_{v,r} = (p_{v,r} - c + S) Q_{v,r}(p_{v,r}, p_{r,v}) - l w_{v,r}^2 \quad \forall v, r \in \{\text{green}\} \tag{12}$$

In the second strategy profile, one concrete producer adopts the green strategy (v), while its competitor opts for the non-green alternative (r). Market demand is assumed to hinge on the pricing strategies of both producers ($p_{v},_{r}$ and $p_{r},_{v}$) and the environmentally conscious activity pursued by the producer employing strategy v. The following equations model the market demand and profit function for the producer utilizing the non-green strategy (Player 1):

$$Q_{v,r} = \phi - \rho p_{r,v} + \sigma p_{v,r} - \lambda_2 w_{v,r} \quad \forall v \in \{\text{non-green}\}, r \in \{\text{green}\} \tag{13}$$

$$\pi_{v,r} = (p_{v,r} - c - T) Q_{v,r}(p_{v,r}, p_{r,v}) \quad \forall v \in \{\text{non-green}\}, r \in \{\text{green}\} \tag{14}$$

Furthermore, in the scenario where Player 1 adopts a non-green strategy while Player 2 opts for a green strategy, the market demand and profit function of the green producer are articulated as follows:

$$Q_{r,v} = \phi - \rho p_{r,v} + \sigma p_{v,r} + \lambda_1 w_{r,v} \quad \forall v \in \{\text{non-green}\}, r \in \{\text{green}\} \tag{15}$$

$$\pi_{r,v} = (p_{r,v} - c + S) Q_{r,v}(p_{r,v}, p_{v,r}) - l w_{r,v}^2 \quad \forall v \in \{\text{non-green}\}, r \in \{\text{green}\} \tag{16}$$

Conclusively, in strategy profile 3, both chosen players within the analyzed symmetric two-player game opt to embrace the non-green strategy, persisting in the production of concrete through traditional methods. Eqs. (17)–(18) elucidate the demand and profit functions in this specific scenario.

$$Q_{v,r} = \phi - \rho p_{v,r} + \sigma p_{r,v} \quad \forall v, r \in \{\text{non-green}\} \tag{17}$$

$$\pi_{v,r} = (p_{v,r} - c - T) Q_{v,r}(p_{v,r}, p_{r,v}) \quad \forall v, r \in \{\text{non-green}\} \tag{18}$$

Furthermore, it is assumed that the primary goal of the government is to minimize the total amount of CO_2 emissions within the concrete production supply chain while considering the social and economic aspects. The mathematical model presented below

Table 3
Pay-off matrix among both players.

			Player 2	
			Green	**Non-green**
			(y)	$(1-y)$
Player 1	Green	(y)	$(\pi_{g,g}, \pi_{g,g})$	$(\pi_{g,ng}, \pi_{ng,g})$
	Non-green	$(1-y)$	$(\pi_{ng,g}, \pi_{g,ng})$	$(\pi_{ng,ng}, \pi_{ng,ng})$

illustrates the government's objective. The model presumes that each type of concrete producers, whether green or non-green, has a minimum profit threshold. If the attained profit falls below this threshold, they may not be willing to comply with the new policy.

$$\begin{aligned} \min Z_3 = {} & \left(\sum_{j=1}^{n} e_j^{\text{gr}} Q_j^{\text{gr}} + \sum_{j=n+1}^{J} e_j^{\text{ng}} Q_j^{\text{ng}} \right) \\ & + \left(\sum_{j=1}^{n} Q_j^{\text{gr}} \left(\frac{3}{100}(e^p + \xi^p d_j) y'_j + \frac{12}{100}(e^c + \zeta^c d'_j) y_j \right) \right) \\ & + \left(\sum_{j=n+1}^{J} \frac{15}{100} Q_j^{\text{ng}} (e^c + \zeta^c d'_j) y'_j \right) \\ \text{s.t.} \quad & \pi_{v,r} \geq L_{v,r} \qquad \forall v, r \in \{\text{green, non-green}\} \\ & \pi^{\text{Gov}} \geq 0 \end{aligned} \tag{19}$$

where the profit function for the government is as Eq. (20).

$$\pi^{\text{Gov}} = \sum_{j \in \text{non-green}} Q_{j'}^{\text{ng}} (T_j - \text{CP}^{\text{ng}}) - \sum_{j \in \text{green}}^{n} Q_j^{\text{gr}} (\text{CP}^{\text{gr}} - S_j) \tag{20}$$

3.4. Evolutionary game model

EGT represents an extension of classical game theory, aimed at elucidating how populations evolve and manifest diverse behaviors across various domains such as economics, finance, and society (Alboszta et al., 2004; Barron, 2024). Unlike traditional game theory, which often assumes that entities, such as corporations, adhere to fixed strategies without considering their evolutionary sustainability, the EGT approach investigates scenarios involving multiple players to determine which strategies will ultimately be adopted by the majority of the population (Xiao and Yu, 2006). This perspective offers a more dynamic framework for understanding how strategies emerge and persist in evolving populations (Johari et al., 2019). After evaluating the environmental impacts of the proposed methods for concrete production and analyzing the LAP by considering all of the current concrete producers, the economic aspects of different strategies should also be considered. Because of the cost of the proposed method and potential governmental penalties, it is highly probable that some producers will not want to use the new method. Therefore, understanding which concrete producers will be more encouraged to use treated plastics over time can help decision-makers in adjusting a comprehensive strategic plan. Given these characteristics, features such as long-term planning, dynamism, and a large number of players make EGT particularly suitable for addressing the complexities of the research problem at hand.

In the proposed model, a population of concrete producers is considered. According to EGT, two of these concrete producers are selected as players. A fundamental EGT model is defined by a set denoted as $E = \{P, S, \pi\}$ where P represents the players, S refers to the strategies available to these players, and π denotes the payoff functions governing the outcomes of the game. Stable strategies in EGT would not be overcome by any other strategy (Barron, 2024). S_g refers to the strategy employed by one group of the population of players, and S_t refers to the strategy employed by the rest of the population. Thus, $u(S_g, S_t)$ measures the expected payoff of strategy S_g against strategy S_t. According to Barron (Barron, 2024), whenever only two pure strategies are employed in the population, the Evolutionarily Stable Strategy (ESS) is defined as follows:

$$u(S^*, S^*) > u(S, S^*) \quad \forall S \in [0,1], S \neq S^* \tag{21}$$

$$u(S^*, S^*) = u(S, S^*) \rightarrow u(S, S) < u(S, S^*) \quad \forall S \neq S^* \tag{22}$$

S^*, an ESS, is characterized by the fulfillment of either conditions in Eqs. (21)–(22). To ensure concrete producer will be convinced to transition to green concrete, it is required to determine the most favorable pricing strategy to attain payoffs exceeding the average benefits. In this context, y represents the proportion of the concrete producers opting for the green strategy, while $(1-y)$ denotes the percentage of them choosing the non-green strategy. As result, the set of strategies includes $S = (y, 1-y)$. Table 3 illustrates the payoff matrix for the players across the strategies under consideration.

Under the first strategy profile where both players select the green concrete, the game model remains identical for both of the two concrete producers. Therefore, the model is assessed solely from the perspective of the first producer. The profit function of the first player is presented as follows:

$$\pi_{(v,r)} = (p_{v,r} - c + S) Q_{v,r}(p_{v,r}, p_{r,v}) - \text{lw}_{v,r}^2 \quad v, r \in \{\text{green}\} \tag{23}$$

To compute the optimal equilibrium of price and demand, the profit function should be concave. By substituting Eqs. (11) into (23), the equation is subsequently redefined as follows.

$$\pi_{v,r} = (p_{v,r} - c + S)(\varphi - \rho p_{v,r} + \sigma p_{r,v} + \lambda_1 w_{v,r} - \lambda_2 w_{r,v}) - \mathrm{lw}_v^2 \quad v, r \in \{\text{green}\} \tag{24}$$

Lemma 1. *Under strategy profile 1, where both concrete producers adopt the green technology, the Nash equilibrium prices of the two aligned manufacturers are:*

$$p^*_{v,r} = \frac{A_2(c\rho - S\rho + \varphi) + A_1}{4\rho^2 - \sigma^2}, \tag{25}$$

$$p^*_{r,v} = \frac{A_2(c\rho - S\rho + \varphi) - A_1}{4\rho^2 - \sigma^2}. \tag{26}$$

The detailed derivation is provided in "Appendix B".

The subsequent proposition is introduced to compare the optimal values of pricing decisions between the two aligned manufacturers under strategy profile 1.

Note. In the entire paper, A_1, A_2, A_3 and B_1, B_2, B_3,B_4 represent changes in the variables. Please refer to "Appendix B" for further information.

Proposition 1. *In Strategy Profile 1, where both producers adopt the green technology, the equilibrium price $p^*_{v,r}$ is increasing in market size ϕ (i.e. $\frac{\partial p^*_{v,r}}{\partial \phi} > 0$). The comparative static with respect to the self-price parameter ρ is conditional. Specifically, $\frac{\partial p^*_{v,r}}{\partial \rho} > 0$ if $\phi < \frac{S\sigma}{2} - A_3$ and $0 < c < \frac{S\sigma - 2\phi - 2A_3}{\sigma}$; otherwise, $\frac{\partial p^*_{v,r}}{\partial \rho} < 0$. The expressions and sufficient conditions are provided in "Appendix B".*

Interpretation. Proposition 1 shows that when both producers adopt the green technology, a larger market size (ϕ) supports a higher equilibrium price, consistent with stronger aggregate willingness-to-pay. The effect of ρ is not uniform: depending on the joint configuration of market size and production cost, the equilibrium price can either increase or decrease with ρ. This highlights that demand sensitivity and cost structure jointly determine how equilibrium pricing responds to changes in own-price effects.

In the second strategy, when the first concrete producer chooses the traditional approach and the second one opts for the green concrete production, the problems encountered by these two matched producers diverge due to their distinct strategies. Consequently, the profit function for the first producer can be articulated as follows:

$$\pi_{v,r} = (p_{v,r} - c - T)(\varphi - \rho p_{v,r} + \sigma p_{r,v} - \lambda_2 w_{r,v}) \quad \text{for } v \in \{\text{non-green}\}, r \in \{\text{green}\} \tag{27}$$

Moreover, the profit function for the second producer is obtained as follows:

$$\pi_{r,v} = (p_{r,v} - c + S)(\varphi - \rho p_{r,v} + \sigma p_{v,r} + \lambda_1 w_{r,v}) - \mathrm{lw}_{r,v}^2 \quad \text{for } v \in \{\text{non-green}\}, r \in \{\text{green}\} \tag{28}$$

Lemma 2. *Under strategy profile 2, where one producer adopts the green technology and the other remains non-green, the Nash equilibrium prices are:*

$$p^*_{v,r} = -\frac{\sigma(c\rho - S\rho + \varphi + w_{r,v}\lambda_1) + 2\rho((c+T)\rho + \varphi - w_{r,v}\lambda_2)}{(-4\rho^2 + \sigma^2)} \tag{29}$$

$$p^*_{r,v} = \frac{\rho\big(2(c-S)\rho + (c+T)\sigma\big) + (2\rho + \sigma)\varphi + w_{r,v}(2\rho\lambda_1 - \sigma\lambda_2)}{4\rho^2 - \sigma^2} \tag{30}$$

The detailed derivation is provided in "Appendix B".

Subsequently, a proposition is put forth to evaluate and contrast the optimal pricing decisions of the two collaborating producers operating under strategy profile 2.

Proposition 2. *In Strategy Profile 2, where one producer is green and the competitor is non-green, equilibrium prices are strategic complements (i.e., $\frac{\partial p^*_{v,r}}{\partial p^*_{r,v}} = \frac{\sigma}{2\rho} > 0$). Moreover, the equilibrium price of the green producer is increasing as green effort increases $w_{r,v}$ (i.e. $\frac{\partial p^*_{r,v}}{\partial w_{r,v}} = \frac{\lambda_1}{2\rho} > 0$).*
Interpretation. *The positive cross-price response implies that an increase in the green producer's equilibrium price relaxes competitive pressure and permits the non-green producer to raise its price as well. In addition, higher green effort $w_{r,v}$ increases the green producer's equilibrium price, indicating that stronger valuation of the green attribute enables a price premium. From the management perspective, actions that strengthen the visibility or perceived value of green attributes can improve the green producer's pricing power, while also affecting overall competitive pricing.*

In the final scenario profile, where both concrete producers opt not to use treated plastics, the problems for producers are identical because they both employ the same strategy. Therefore, in this strategy profile, we model the problem for producer 1 (player 1), where producer 1 seeks to optimize the values of its pricing $p_{v,r}$ as follows:

$$\pi_{(v,r)} = (p_{(v,r)} - c - T)(\varphi - \rho p_{(v,r)} + \sigma p_{(r,v)}), \quad v, r \in \{\text{non-green}\} \tag{31}$$

Lemma 3. *Under strategy profile 3, where both producers remain non-green, the optimal concrete price is:*

$$p^*_{(v,r)} = \frac{(c+T)\rho + \varphi}{2\rho - \sigma}, \quad v, r \in \{\text{non-green}\}. \tag{32}$$

The detailed derivation is provided in "Appendix B".

Proposition 3. *In Strategy Profile 3, where both producers remain non-green, the equilibrium price $p^*_{v,r}$ increases with market size ϕ and cross-price parameter σ, and decreases with the self-price parameter ρ:*

$$\frac{\partial p^*_{v,r}}{\partial \phi} > 0, \qquad \frac{\partial p^*_{v,r}}{\partial \sigma} > 0, \qquad \frac{\partial p^*_{v,r}}{\partial \rho} < 0.$$

In addition, the equilibrium price is increasing in production cost c (i.e. $\frac{\partial p^*_{v,r}}{\partial c} > 0$).

Interpretation. *When both producers remain non-green, a larger market supports higher equilibrium prices, whereas stronger own-price effects (ρ) discipline equilibrium prices downward. The positive role of σ reflects stronger strategic interdependence under this demand structure. Although higher production cost c increases the equilibrium price through pass-through, it can still compress margins and weaken profitability, particularly when demand is price-sensitive.*

3.5. Location-allocation model (model 2)

As mentioned earlier, the product's price and profit are two main variables for concrete producers that can assist them in making the best decisions. After calculating the optimal price using a game theory approach in the previous section, a new mathematical model is proposed in this section to satisfy market demand while maximizing the profit of the entire supply chain. This model suggests which producer remain active, and which one discontinues, and the capacity of the concrete producers that remain open will be increased. Eqs.(36)-(47) show the mathematical model of the final phase.

$$\begin{aligned} \max Z_4 = {} & \sum_{j=1}^{|J|} \partial_j p_j - \left(\frac{1}{\eta} \sum_{g=1}^{G} \sum_{m=1}^{M} y^L_{gm} \omega^f_m + \sum_{g=1}^{G} \sum_{m=1}^{M} x^L_{gm} \alpha_g (\omega^R_m + \omega^O_m) \right) \\ & - \left(\sum_{g=1}^{G} \sum_{m=1}^{M} x^L_{gm} \zeta^L_{gm} d^L_{gm} + \sum_{j=1}^{J} \sum_{t=1}^{T} x^C_{tj} \zeta^C_{tj} d^C_{tj} + \sum_{m=1}^{M} \sum_{j=1}^{J} x^R_{mj} \zeta^R_{mj} d^R_{mj} \right) - \sum_{j=1}^{J} \partial_j U^C_j \end{aligned} \tag{33}$$

$s.t.:$

$$\sum_{m=1}^{|M|} x^R_{mj} \geq \beta^R \partial_j, \qquad \forall j \in J \tag{34}$$

$$\sum_{t=1}^{|T|} x^C_{tj} \geq \beta^C \partial_j, \qquad \forall j \in J \tag{35}$$

$$\partial_j \geq D_j, \qquad \forall j \in J \tag{36}$$

$$\sum_{j=1}^{|J|} \partial_j \geq \sum_{j=1}^{|J|} D_j, \tag{37}$$

$$\sum_{j}^{J} \gamma_j \leq n, \tag{38}$$

$$x^L_{gm} \leq M y^L_{gm}, \qquad \forall g \in G, \forall m \in M \tag{39}$$

$$\partial_j \leq M \gamma_j, \qquad \forall j \in J \tag{40}$$

$$x^R_{mj} \leq M \gamma_j, \qquad \forall m \in M, \forall j \in J \tag{41}$$

$$x^C_{tj} \leq M \gamma_j, \qquad \forall t \in T, \forall j \in J \tag{42}$$

$$\gamma_j, y^L_{gm} \in \{0, 1\} \tag{43}$$

$$x^C_{tj} \geq 0, \quad x^R_{mj} \geq 0, \quad x^L_{gm} \geq 0, \quad \delta_m \geq 0, \quad \partial_j \geq 0 \tag{44}$$

The objective function in Eq. (33) maximizes the profit of concrete producers. The first term in this equation refers to the revenue generated by green concrete producers. The second term represents fixed and operational costs in the WTCs where $\eta = 30$. The third term accounts for transportation costs, and finally, the last term corresponds to the cost of concrete production. Given that the selected concrete producers in this model are environmentally friendly, Eq. (34) specifies that at least 3% of the input materials of the concrete producers should be allocated to treated plastics. Moreover, Eq. (35) guarantees that 12% of the capacity will be allocated to cement as well. Eq. (36) indicates that all concrete producers should have enough capacity, at least equal to the amount of demand, in order to satisfy the total market demand. Eqs. (37)–(38) stipulate that each concrete producer should possess sufficient capacity to meet the quantity demanded by the market. In addition, Eq. (39) addresses the maximum number of concrete producers to be established

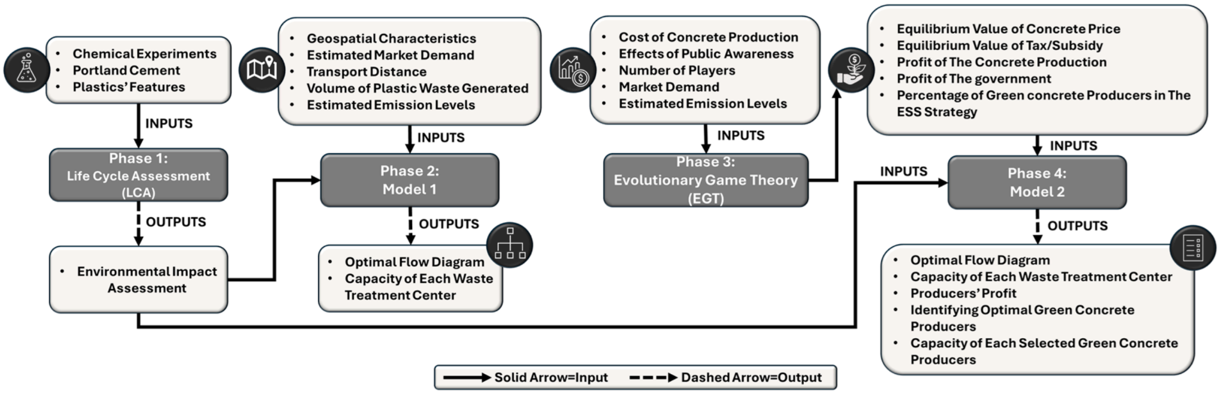


Fig. 7. Relationship between models in the proposed framework (arrows represent input\output of each phase).

in this state as green producers. Eqs.(40)-(42) indicate that the capacity will be assigned only when its related facility is established. Finally, the characteristics of the variables in the proposed model are delineated by Eqs. (43)–(44). Moreover, it should be mentioned that to apply the capacity of each plastic resource and waste treatment center, as well as to show the useful amount of plastics that can be used by treatment centers, Eqs. (3)–(5) from the first model should be incorporated into this model as well.

3.6. Framework synthesis and empirical operationalization

Section 3 presents an integrated framework linking environmental accounting, strategic market behavior, and system-level evaluation to assess when recycled plastic in concrete delivers both environmental and economic benefits. The section is intentionally structured as a modeling pipeline in which each component plays a distinct role and provides inputs that are required by the next component. Fig. 7 summarizes this workflow and highlights how the models jointly support the empirical/numerical investigations reported in Section 4.

We begin with Model 1 because the central question of this study is not only whether recycled plastic improves environmental performance, but also whether such improvements remain economically viable under realistic market conditions. Model 1 therefore serves as the environmental–economic accounting backbone of the framework: it translates the use of recycled plastic into comparable cost and emissions terms and establishes the baseline trade-offs that any adoption strategy must confront. These quantities are not treated as abstract metrics; rather, they function as economically meaningful primitives that can shape firms' strategic incentives, such as the feasibility of pricing a green product competitively when production costs or demand conditions vary.

We then introduce the evolutionary game-theoretic (EGT) analysis to capture competitive adoption and pricing dynamics that cannot be inferred from accounting results alone. Even if adding recycled plastic to concrete is environmentally advantageous, its diffusion depends on whether firms can sustain equilibrium outcomes under competition, demand sensitivity, and green-effort considerations. The EGT component provides this behavioral layer by characterizing equilibrium strategy profiles and comparative statics, thereby clarifying which market forces amplify or suppress incentives to adopt green technology, and which levers (e.g., demand responsiveness, competitive interaction, and green effort) most strongly affect equilibrium pricing and adoption tendencies.

Finally, Model 2 extends the framework from equilibrium characterization to system-level evaluation and scenario-based assessment. While the EGT results explain how firms behave strategically, Model 2 consolidates the outputs into a structured evaluation layer that supports comparative scenario analysis and enables a transparent mapping from strategic outcomes to measurable system implications. This final stage is essential for interpreting the framework in terms of practical decision support: it organizes the model outputs in a way that directly supports the empirical/numerical analysis and ensures that economic outcomes (e.g., equilibrium prices and implied demand) and environmental outcomes (e.g., emissions impacts) are assessed consistently across scenarios.

To make the role of each modeling component explicit, Table 4 provides a compact synthesis of the primary benefit each component brings to the framework and its methodological contribution. Building on this integrated pipeline, Section 4 operationalizes the framework by parameterizing the key primitives, computing equilibrium outcomes across the strategy profiles, and conducting scenario and sensitivity analyses guided by the drivers highlighted in Section 3. In doing so, Section 4 evaluates the economic–environmental trade-offs under empirically grounded conditions and demonstrates how the mechanisms identified in Section 3 translate into interpretable outcomes for decision-makers.

4. Numerical analysis

4.1. Case data

To evaluate the proposed mathematical framework, a dataset based on real data in HRM, Canada is chosen. Almost 1,100,000 people are living in this province, with around 430,000 residing in HRM. Nova Scotia is one of the provinces in Canada with wide-ranging immigration plans, which have influenced the trend of population growth. It is projected that the city population will reach

Table 4

Summary of modeling components and their role in the integrated framework.

Component	Benefit to the integrated framework	Methodological contribution
Model 1	Establishes a consistent environmental–economic accounting basis for evaluating recycled-plastic concrete, translating material choices into comparable cost and emissions terms.	**Integration of LCA into Network Design:** Bridges the gap between material-level environmental assessment and system-level supply chain optimization, allowing specific chemical treatment parameters to directly constrain logistical decision-making.
EGT	Captures competitive adoption and pricing behavior under market interaction and demand sensitivity, clarifying when green adoption is strategically stable.	**Dynamic Behavioral Modeling:** Endogenizes market demand and producer adoption within a construction supply chain, moving beyond static optimization to capture the temporal evolution of green strategies under governance (tax/subsidy) and social (awareness) pressures.
Model 2	Consolidates equilibrium outcomes into a structured evaluation layer for system-level interpretation and scenario-based assessment.	**ESG-Oriented System Synthesis:** Formalizes a feedback loop between strategic market behavior and operational infrastructure planning, demonstrating how social and governance mechanisms can be quantified to reshape the cost-emission trade-off in facility location problems.

650,000 by 2035 (Council, Halifax Regional, 2022). The province has announced to reach zero pollution levels by 2050 in the published net-zero plan (Globemd, 2021). According to the plan, HRM should reduce around 1.4 MtCO_2e by 2030, which is almost 75% of its value in 2016. Multiple sectors should contribute to this strategy. As the population grows, building new apartments becomes essential. Moreover, according to the plans of the authorities in HRM, approximately 320 houses should be built each year. In addition, more population translates into more consumption and more waste, particularly plastics waste. These facts show that without considering new strategies, HRM can face serious emission issues soon. Therefore, by considering the proposed framework, the authorities of this province can manage upcoming environmental and economic challenges. The reviewed case in HRM encompasses a total of 13 sites, comprising four plastic-related manufacturers and nine landfill sites, all identified as potential sources of plastic waste. Notably, ten of these sites are situated within Nova Scotia, with the remaining three situated in neighboring province, New Brunswick. The reason for involving three sites from New Brunswick is our initial analysis, which shows current plastic waste in the province could be insufficient to satisfy the market demand for green concrete. Fig. 8 illustrates the locations of the selected facilities in this case study, and more details of these facilities are provided in Appendix C (Table C.1).

In terms of regional context, several factors shape the applicability of this case study. Nova Scotia has implemented an Extended Producer Responsibility (EPR) program for packaging and paper products, which holds producers accountable for the collection, sorting, and processing of household plastic waste. As a result, the policy has significantly strengthened the province's recycling infrastructure (Diggle et al., 2023). The region operates nine material recovery facilities serving approximately one million residents, supported by comprehensive curbside collection systems, including blue bins for PET, HDPE, and LDPE plastic resins (Helio Urban Development, 2025).

Despite having a well-established residential recycling system, the province still lacks sufficient capacity for industrial-scale chemical treatment or the processing of recycled plastics into construction-grade materials. Meanwhile, the HRM is advancing its sustainability agenda through the HalifACT climate action plan, which includes a commitment to net-zero building standards by 2030. Initiatives such as the Solar City program further incentivize green construction practices by promoting energy efficiency and the use of sustainable materials (Halifax Regional Municipality, 2024). Taken together, these features (i.e., a robust recycling infrastructure, evolving green building incentives, and a growing emphasis on low-carbon construction) provide strong contextual support for the case. However, the broader generalizability of the findings depends on region-specific variables, including the composition of local plastic waste streams, existing policy frameworks, and the readiness of the construction industry to adopt recycled materials.

Furthermore, it is worth noting that the proposed mathematical models, within the framework, are solved using the Gurobi solver in Python, and Mathematica software is used for the game theory models.

4.2. Results

As mentioned already, in this study, two forms of experiments have been considered for the treatment processing of plastics: 1) Phosphonate in water 2) Carboxylate. In the first experiment, 4-aminobenzyl phosphonic acid was used as the arylamine precursor. The mixture was prepared in deionized water, cooled in an ice bath, and treated with sodium nitrite to convert the amine group to an aryldiazonium cation. This reaction was carried out in an acidic environment to maintain the stability of the diazonium cations. Subsequently, hypo-phosphorous acid was added, resulting in the transformation of aryldiazonium cations into stable radicals, which then interacted with the surface of fibers placed in the solution. In the second experiment, P-aminobenzoic acid served as the arylamine precursor. The procedure similarly involved preparing the mixture in deionized water, cooling it in an ice bath, and adding sodium nitrite, followed by the addition of hypo-phosphorous acid to produce stable radicals that interacted with the fibers' surfaces. The proposed approach in terms of concrete production is simulated in SimaPro. Fig. 9. illustrates the results of damage assessment on three aspects: Human health, ecosystem, resources.

Moreover, the normalization results are also shown in the Fig. 10. SimaPro uses normalization factors to help users understand the relative importance of various environmental impacts. By comparing the environmental performance of a product or process to

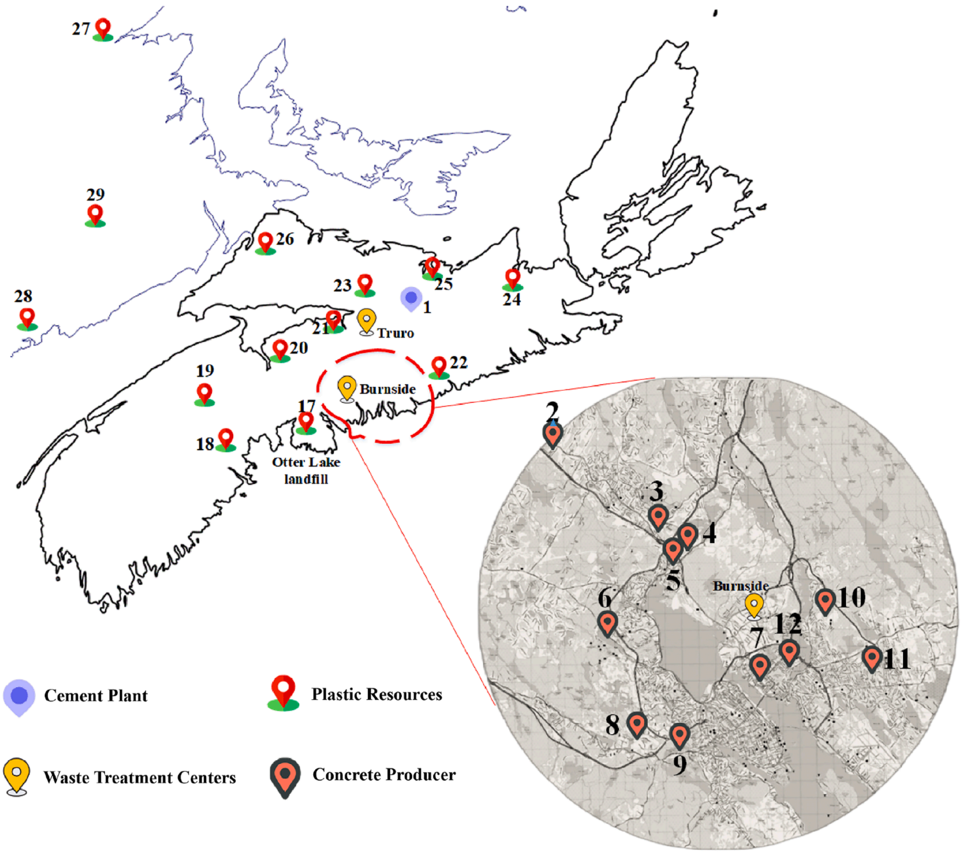
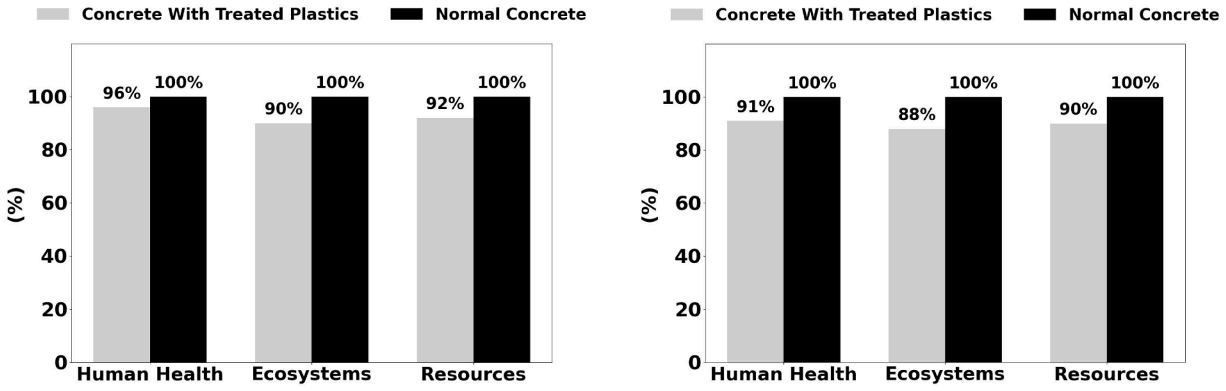


Fig. 8. Location of the selected cites, Nova Scotia, Canada.



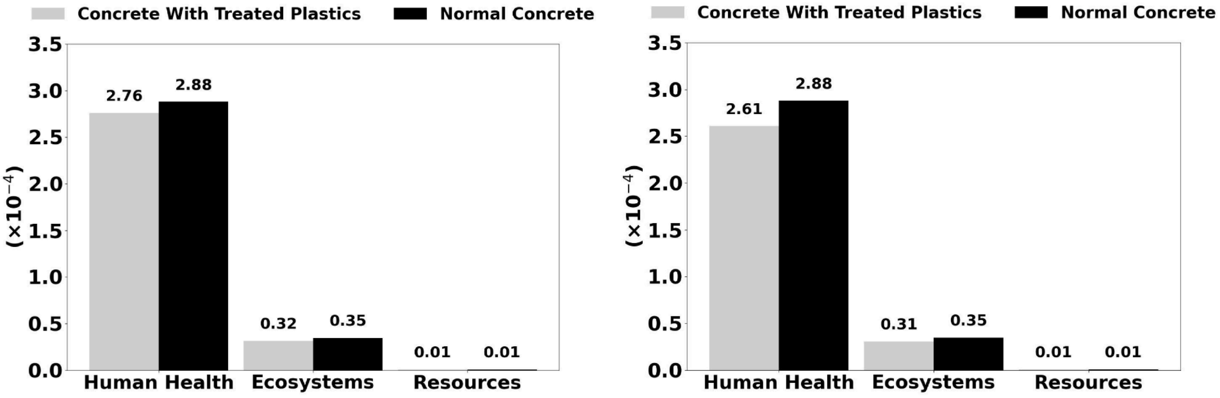
(a) Results related to the first experiment.

(b) Results related to the second experiment.

Fig. 9. The results of damage assessment in both experiments.

these reference values, practitioners can identify which environmental aspects have the most significant contributions and prioritize areas for improvement or further investigation.

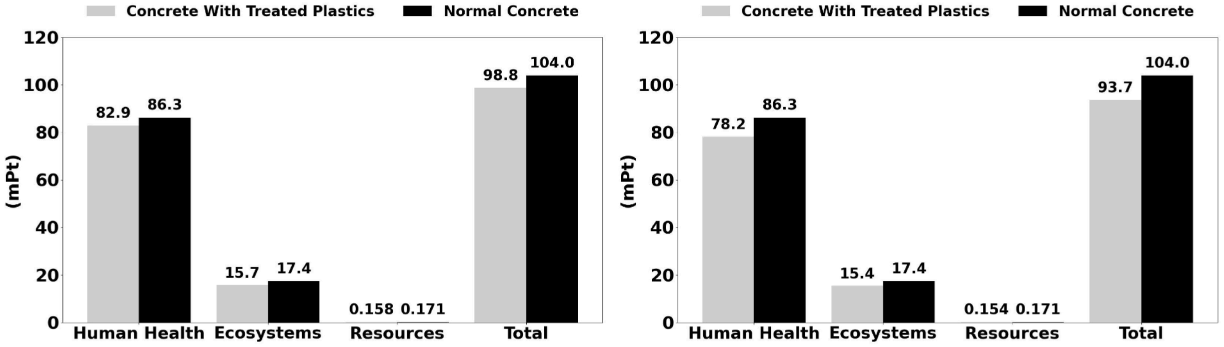
The concept of a single point, Fig. 11, is related to the idea of aggregation, where multiple environmental impact categories are combined into a single score. This can be achieved through a method called “weighting,” where each impact category is assigned a weight based on its perceived importance, and the individual impact scores are then multiplied by these weights and summed to obtain an overall score. The single point can represent environmental performance in a unit that is more intuitive or relevant for decision-makers.



(a) Results related to the first experiment.

(b) Results related to the second experiment.

Fig. 10. The results of normalization factor in both experiments.



(a) Results related to the first experiment.

(b) Results related to the second experiment.

Fig. 11. The results of single point factor in both experiments.

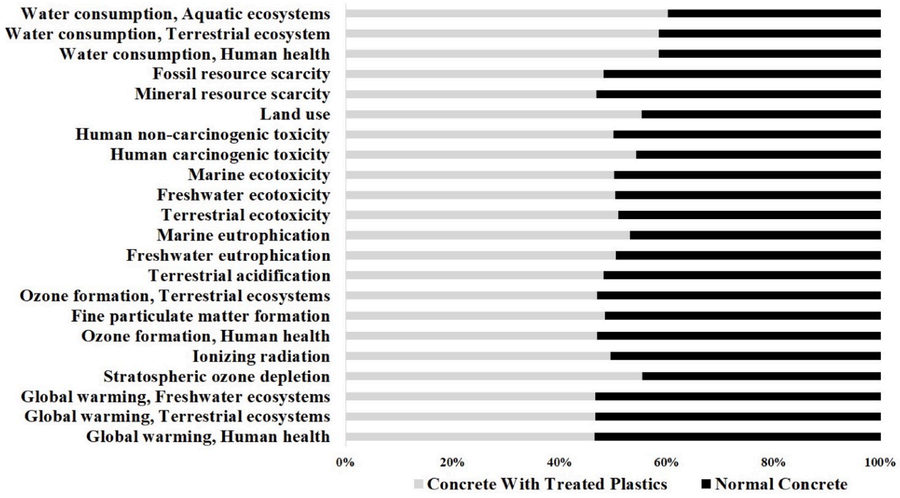
Categorical analysis within the context of LCA allows for the classification of environmental impacts into distinct categories-typically including human health, ecosystem quality, and resource depletion. This type of analysis provides insight into which specific environmental dimensions are most affected by a given process or product. By examining category-level impacts, it becomes possible to pinpoint the stages of the life cycle that contribute most to environmental burdens and identify opportunities for targeted improvement. In this study, categorical analysis was used to compare conventional concrete production with the proposed method of incorporating treated plastics. According to Fig. 12, the findings show notable reductions in several key categories, particularly in impacts related to human health and fossil resource use, underscoring the broader environmental advantages of substituting a portion of cement with recycled plastics in concrete manufacturing.

As result, based on the simulation results of two experiments from SimaPro, it was found that the experiments were efficient in reducing the environmental impacts to the human health, the ecosystem, and resource utilization. The proposed method of integrating treated plastics in concrete outperformed the conventional method used for producing concrete. Therefore, the new concrete production method is potentially more environmentally friendly.

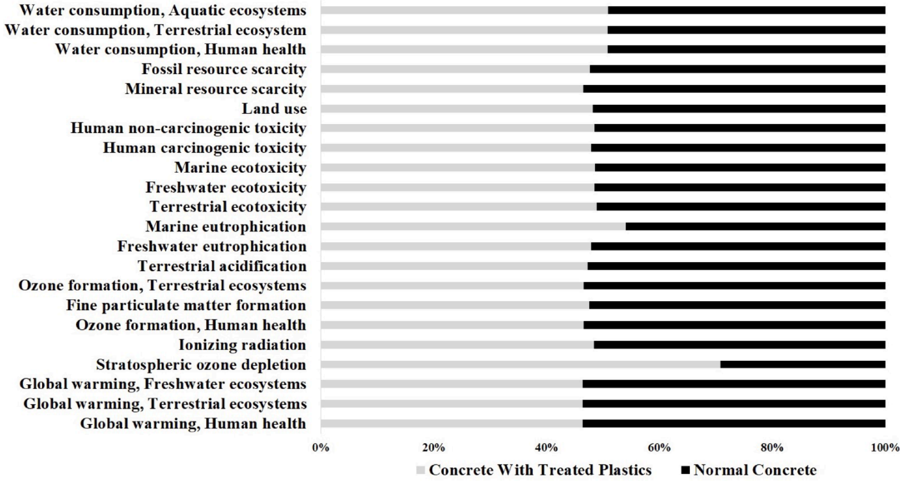
The proposed bi-objective model (model 1) is solved using the augmented ϵ-constraints method (See “Appendix A”). The results are presented in Fig. 13.

The Pareto front represents a set of solutions that are considered non-dominated in a multi-objective optimization problem. In this research, we have two objectives: minimizing total supply chain cost (the first objective function) and minimizing CO_2 emissions (the second objective function). The Pareto front shows a trade-off between these two conflicting objectives. Table 5 shows the values of the objective functions at the selected Pareto solutions (1 to 4).

In the Pareto front illustrated in Fig. 13, the leftmost solution represents the lowest total system cost (3.74×10^7), but it is associated with the highest level of CO_2 emissions (7.26×10^6). This solution may therefore be preferred in situations where economic considerations dominate decision-making. At the opposite extreme, the rightmost solution yields the lowest emission level (7.20×10^6), but this improvement is achieved at the expense of a higher total cost (3.76×10^7), reflecting the inherent trade-off between economic and environmental objectives.



(a) Results related to the first experiment.



(b) Results related to the second experiment.

Fig. 12. Categorical breakdown of environmental impacts across key impact categories.

Table 5
Value of objective functions at selected Pareto solutions.

No. Pareto solution	Objective function Z_1 (Cost)	Objective function Z_2 (CO_2 emission)
1	37,350,837.51	7,264,892.43
2	37,433,881.27	7,233,161.34
3	37,546,546.60	7,209,961.47
4	37,587,342.38	7,198,283.29

An examination of the rate of change between the extreme solutions (from Pareto point 1 to point 4) indicates that a reduction of approximately 0.56% in CO_2 emissions requires an increase of about 0.86% in total system cost. This suggests that relatively modest additional investments can lead to meaningful environmental improvements within the range of efficient solutions identified by the model.

Further insights emerge from the intermediate Pareto solutions. In particular, points 2 and 3 exhibit the most balanced trade-offs between cost and emissions. Moving from point 1 to point 2, a small increase of approximately 0.09% in cost leads to a reduction of about 0.15% in emissions. Similarly, at point 3, an increase in cost of roughly 0.10% results in a 0.12% decrease in total CO_2 emissions. These solutions therefore offer attractive compromise options for decision-makers seeking emission reductions without incurring substantial additional costs.

The overall shape of the Pareto front further supports this interpretation. Initially, increases in cost lead to relatively steep reductions in emissions; however, as one moves further along the front toward higher-cost solutions, the marginal emission reductions

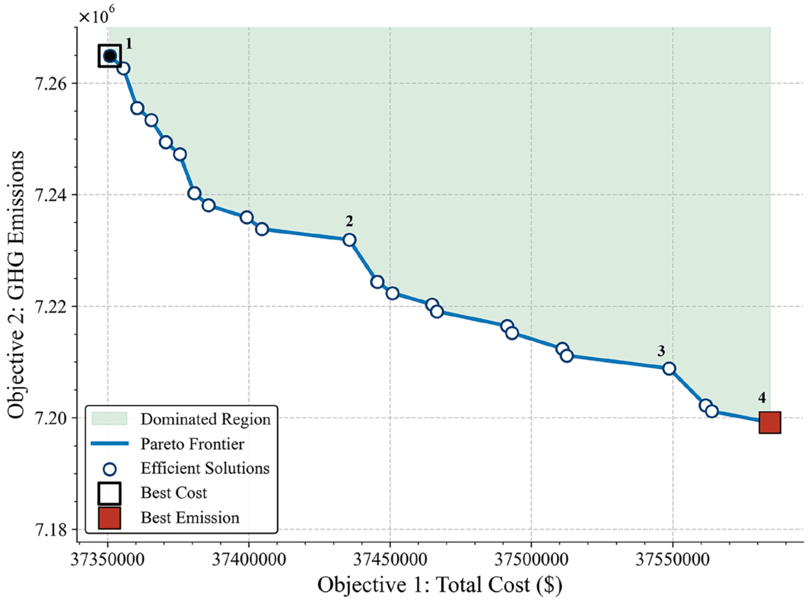


Fig. 13. The optimal Pareto front solutions for Model 1.

Table 6
Value of x_{mj}^R at selected Pareto solutions.

(m, j) Pair	Pareto solution 1	Pareto solution 2	Pareto solution 3	Pareto solution 4
(1,1)	0	477.2	615.17	1630.64
(1,2)	0	1630.64	1630.64	1630.64
(1,3)	0	0	1630.64	1630.64
(1,4)	0	566.43	1630.64	1630.64
(1,9)	0	0	0	83.9
(2,1)	0	1153.44	1015.47	0
(2,2)	1153.44	0	0	0
(2,5)	1630.64	1630.64	1630.64	1630.64
(2,6)	0	0	137.97	1153.44
(2,7)	1630.64	1630.64	1630.64	1630.64
(2,8)	1630.64	1630.64	1630.64	1630.64
(2,10)	1630.64	1630.64	1630.64	1630.64
(3,1)	1630.64	0	0	0
(3,2)	477.2	0	0	0
(3,3)	1630.64	1630.64	0	0
(3,4)	1630.64	1064.21	0	0
(3,6)	1630.64	1630.64	1492.67	477.2
(3,9)	1630.64	1630.64	1630.64	1546.74
(3,11)	1630.64	1630.64	1630.64	1630.64

diminish. This pattern indicates diminishing returns, whereby achieving additional environmental improvements requires increasingly larger cost increases. Overall, when sustainability is an important consideration, Pareto solutions 2 and 3 represent the most favorable options. In contrast, when either economic efficiency or environmental performance is prioritized exclusively, solutions 1 and 4 emerge as the preferred choices, respectively. The values of the decision variables at each point are also shown in Tables 6 and 7.

Solutions 1 and 3 take a more varied strategy to buying treated plastic from several sources, as Table 6 demonstrates. This may indicate a risk-balancing and supply-side stability strategy. Furthermore, the focus on particular centers in solutions 2 and 4 may refer to an emphasis on cost effectiveness or lowering emissions by utilizing the advantages or close proximity of particular locations. The selection of combinations for higher emission points, such as (2,7) and (3,11), implies that, in some circumstances, these centers may provide financial advantages that outweigh greater emissions.

As demonstrated in Table 7 , when there are several suppliers, like $g = 13$ to $g = 17$, the values are constant throughout. This suggests that these sets are essential and well-balanced across various strategies. Moreover, in solutions 2 and 3, the values of the variables are almost the same, except that (12,3) in solution 3 has a value of 0, while (12,1) in solution 2, which was 0, has a value of 2981.91. This suggests that, from an economic perspective at solution 3, the model chooses the closest treatment center to the supplier.

Table 7
Value of x_{gm}^{L} at selected Pareto solutions.

(g, m)	Pareto solution 1	Pareto solution 2	Pareto solution 3	Pareto solution 4
(1, 2)	8080	8080	8080	8080
(2, 3)	93.45	93.45	93.45	93.45
(3, 3)	93.45	93.45	93.45	93.45
(4, 3)	1596.22	1596.22	1596.22	1596.22
(5, 3)	645.62	645.62	645.62	645.62
(6, 3)	303.45	303.45	303.45	303.45
(7, 1)	0	994.76	994.76	994.76
(7, 3)	994.76	0	0	0
(8, 1)	0	0	0	80.33
(8, 3)	80.33	80.33	80.33	0
(9, 1)	0	0	0	558.62
(9, 3)	558.62	558.62	558.62	0
(10, 1)	0	0	0	518.28
(10, 3)	518.28	518.28	518.28	0
(11, 1)	0	1820.26	1820.26	1820.26
(11, 3)	1820.26	0	0	0
(12, 1)	0	0	2981.91	2981.91
(12, 3)	2981.91	2981.91	0	0
(13, 3)	100.95	100.95	100.95	100.95
(14, 3)	303.45	303.45	303.45	303.45
(15, 3)	303.45	303.45	303.45	303.45
(16, 3)	103.45	103.45	103.45	103.45
(17, 3)	303.45	303.45	303.45	303.45

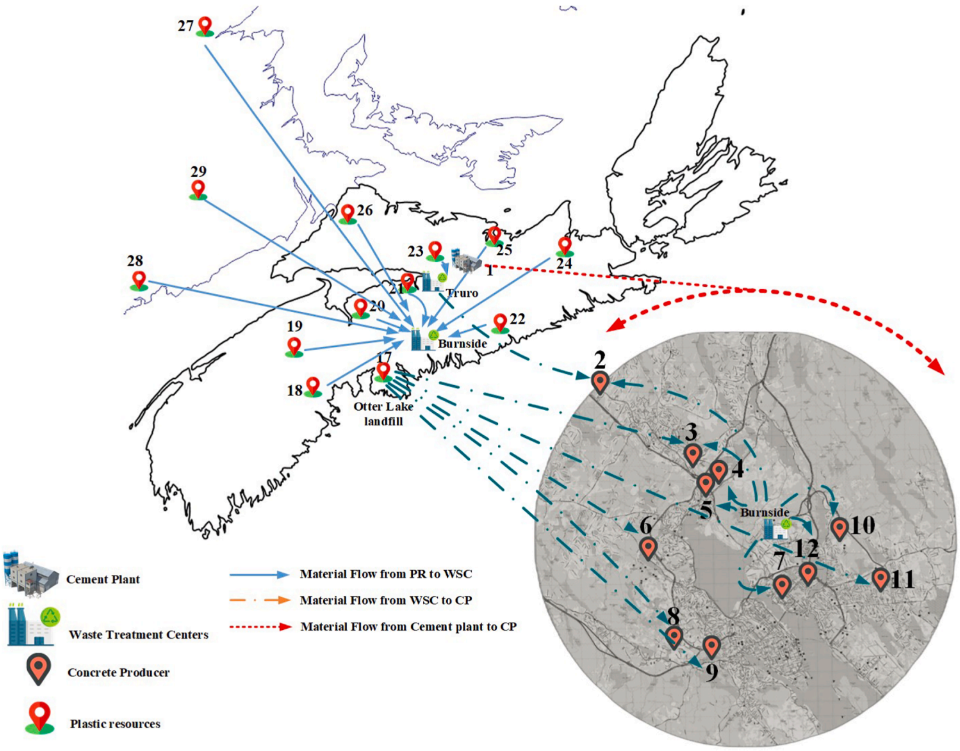


Fig. 14. The graphical presentation of the solutions for Model 1.

Fig. 14 visualizes the optimal solutions from the first model. Considering the results, all candidate locations for waste treatment sites will be opened. According to the numerical results, Truro will have the lowest treatment capacity, satisfying only 61% of the total plastic needs of the first concrete producer (number 2 on the map). At the Otter Lake landfill, treatment will only be conducted on the plastics present within this landfill. This result is promising because there will be no additional costs, such as transportation. The third location, Burnside, plays a significant role in this model, as almost 52% of all plastics will be collected there.

Table 8
Comparing game theory results under various strategy profiles.

Decision Variables	Scenario 1	Scenario 2	Scenario 3	ESS(green, non-green)
Selling price for the first concrete producer ($/ton)	51.91	95.72	112.1	
Selling price for the second concrete producer ($/ton)	51.91	68.6	112.1	
Demand of the first concrete producer (ton)	63.81	0.004	7.72×10^{-6}	
Demand of the second concrete producer (ton)	63.68	97.2	7.72×10^{-6}	
Profit of the first concrete producer ($/ton)	2035.95	8×10^{-6}	0.0028	
Profit of the second concrete producer ($/ton)	2027.61	4724.18	0.0028	
Tax paid by the first concrete producer ($/ton)	–	73.22	89.6	
Tax paid by the second concrete producer ($/ton)	–	–	89.6	
Subsidy received by the first concrete producer ($/ton)	2.5	–	–	
Subsidy received by the second concrete producer ($/ton)	2.5	2.5	–	
The percentage of the concrete producers using green strategies (%)	–	–	–	(0.64, 0.36)

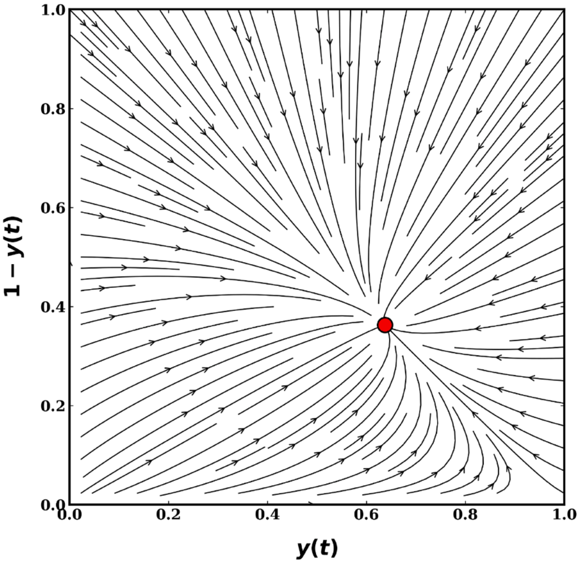


Fig. 15. Convergence trajectory of $\frac{dx}{x(t)}$ toward ESS over time.

Following the sequence of models in Fig. 7, the next step is applying the game theory model. The results of the game theory-based model are presented in Table 7. “Appendix C” contains more details on the parameter values and additional sensitivity analysis.

Table 8 shows the ESS is determined at $x = 0.64$, suggesting that a significant number of concrete producers (64%) will opt for the green strategy. This outcome underscores the practicality of employing the EGT approach within a group of concrete producers with diverse strategies. It indicates that opting for the strategy involving the collective treatment of plastics can be a stable evolutionary choice, implying that the green strategy is likely to prevail over time.

Moreover, a comparison of all three strategies illustrates that when both selected concrete producers choose to use treated plastics, the price of the final concrete is lower than in other strategy profiles. However, if even one of the producers chooses not to adopt green practices, the prices for both producers increase. Nevertheless, the price for non-green concrete producers is significantly higher, approximately 54%, than the green ones. This difference can be attributed to the penalties imposed by the government on non-green producers. In the last strategy profile, where the government’s primary objective is to minimize the total amount of pollution in the supply chain, a substantial tax of $112 is allocated to the producers, resulting in their profits approaching zero. It is important to note that when a producer opts to incorporate treated plastics into its concrete, the government provides a subsidy of around 3$/ton to encourage the continued use of green technologies.

Fig. 15 illustrates the temporal convergence of strategies employed by the concrete producers towards the ESS solution. The depicted arrows signify the trajectory of strategy frequencies over time. Regardless of the initial scenario within the square $(y(t), (1 - y(t))) \in (0, 1) \times (0, 1)$, the frequencies of strategies consistently converge to the ESS solution at the point $(y(t) = 0.63,\ 1 - y(t) = 0.37)$. This shows that approximately 63% of the concrete producers will adopt treated plastics in concrete production (7 out of the 11 producers in this case study), while the remaining 37% will continue producing in a traditional way. Furthermore, Fig. 16 provides insights into the dynamics of the strategies, representing $\frac{dx}{x(t)}$ for concrete producers across four distinct initial conditions. Notably, each initial condition results in a trajectory state, with two positioned on the boundaries and two located within the interval $(0, 1)$. As depicted in these figures, trajectories originating within the interval converge towards the steady state (i.e., $y(t) = 0.63$) over time, while those starting on the boundaries remain in that state indefinitely.

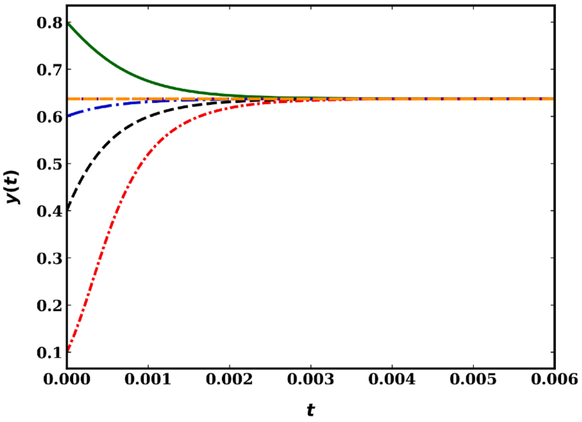


Fig. 16. Direction field and trajectories for $\frac{dx}{x(t)}$ over time (year) under five initial conditions.

Table 9
Optimal values of the capacity of WTCs.

Decision Variables	Location-allocation model 1 (ton)	Location-allocation model 2 (ton)
δ_1	994.76	0
δ_2	8080.0	8080.0
δ_3	9806.34	10,801.1

Table 10
Optimal values of the capacity of concrete producers.

Decision variables	Value (ton)
σ_1	0
σ_2	419,146.1
σ_3	81,531.82
σ_4	81,531.82
σ_5	81,531.82
σ_6	81,531.82
σ_7	0
σ_8	0
σ_9	81,531.82
σ_{10}	0
σ_{11}	81,531.82

The next step, as shown in Fig. 7, the second location-allocation model is applied. In this model, the capacity of the WTCs is one of the decision variables. Table 9 shows the results of δ, the WTCs' capacity, in each scenario. Recalling the results of the first model, all three potential locations were chosen to be opened. However, in the second model, only two locations close to HRM are considered as WTCs. In both models, the capacity of the Otter Lake Landfill remains consistent at 8080 tons. This indicates that all plastics accumulated at this facility must be managed to meet the needs of concrete producers. However, the situation differs for Truro and Burnside. While Truro is designated as one of the WTCs in the first model, with a capacity of 994.76 tons, it is not selected as such in the second model. Consequently, Truro's contribution is redirected to Burnside, increasing its capacity from 9806.34 tons in model 1 to 10801.1 tons in model 2.

As discussed before, the game theory model suggested that only 63% of the concrete producers (7 out of 11) transition to the use of treated plastics. However, the total market demand remains unchanged. Therefore, the operational concrete producers and their capacities should be identified to meet the market demand. The second location-allocation model decides the capacity of each open concrete producer, as presented in Fig. 7.

Table 10 shows that producers 2, 3, 4, 5, 6, 9, and 11 will adopt green policies and continue to use treated plastics. Additionally, except for producer 2 with a capacity of 419146.1 ton, the remaining producers will share the same capacity (81531.82 ton). Fig. 17 illustrates the final result of the revised model in network form. According to the numerical results, plastic supplier 23 that in the first model selected Truro, in the revised model will transfer its plastics to the Burnside. Similar to the first model, Burnside plays a key role in the network, with almost half of the total plastics being collected at this site for treatment.

The effects of the number of opened concrete producers in the second model on the optimum values of the objective functions have been analyzed. Table 11 illustrates the objective function values in the second location-allocation model. The results show that by increasing the number of green concrete producers the profit of the supply chain improves, albeit the effect is not particularly

Table 11
Sensitivity of profit function of concrete producers with respect to the number of opened green concrete producers.

NO. opened concrete producers	Main objective function ($\times 10^7$\$)	Environmental objective function ($\times 10^6$ CO_2/ton)
7	1.78	6.75
8	1.79	6.93
9	1.98	7.1
10	1.95	7.18
11	1.95	7.3

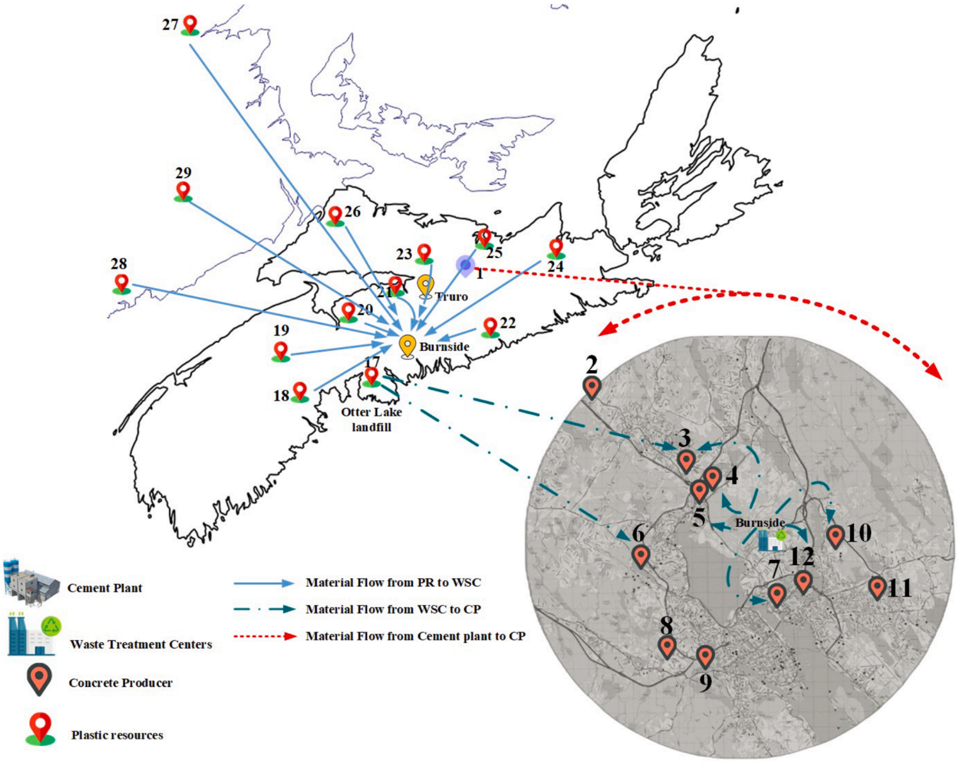


Fig. 17. Graphical results of problem solving using the revised model.

Table 12
Comparison of total system cost and emissions under different production methods.

	Absolute Values			Normalized Values		
Metric	Conventional Production	Model 1	Model 2	Conventional Production (%)	Model 1 (%)	Model 2 (%)
Total System Cost ($\times 10^7$\$)	4.82	3.73	3.89	100.00	77.46	80.82
Emission ($\times 10^6$ CO_2/ton)	9.79	7.26	6.75	100.00	74.20	69.00

substantial. However, this shift can directly impact the environment, as evidenced by the increase in CO_2 emissions from 6.75 MCO_2/ton to 7.3 MCO_2/ton for 7 and 11 producers, respectively. The main reason influencing this variation is probably associated with transportation. Model 1 underscores the significant impact of transportation on environmental factors. Reducing the number of WTCs to 7 decreases the overall transportation distance, which consequently leads to lower emissions.

While the preceding analysis focuses on the behavior of the revised location-allocation model and highlights the role of transportation and network configuration in shaping environmental outcomes, it does not fully reflect the broader impact of ESG-oriented mechanisms on overall system performance. To provide this perspective, we next compare the results of the conventional production setting, the plastic-modified system with an environmental focus (Model 1), and the proposed ESG-integrated framework (Model 2). Table 12 summarizes the corresponding cost and emission outcomes, offering a system-level view of how governance and behavioral mechanisms embedded in the proposed model influence sustainability performance.

Looking beyond individual environmental measures, the results suggest that embedding ESG considerations directly into supply chain design can lead to tangible system-level improvements. As shown in Table 12, the comparison across the three configurations (i.e., conventional concrete production (Model 0), plastic-modified concrete without coordinated ESG-oriented decisions (Model 1), and the proposed ESG-integrated framework (Model 2)) reveals that while Model 1 already lowers emissions through material substitution, Model 2 achieves further emission reductions without a commensurate increase in total system cost. This pattern indicates that the benefits of ESG integration extend beyond the choice of greener inputs and instead arise from better coordination across waste management, logistics, infrastructure investment, and production decisions. From a managerial standpoint, this finding underscores that ESG objectives can be incorporated into strategic supply chain planning in a way that supports environmental goals while remaining economically viable.

4.3. Managerial insights

Evaluating the proposed framework and analyzing the results for the reviewed case, a set of important managerial insights are proposed in this section.

- Using treated plastics in concrete production positively affects the environment. The reduction in the emission surpasses the extra pollution caused in the recycling procedure at waste treatment sites. The LCA results for both experiments (i.e., Phosphonate in water and Carboxylate) indicate an average decrease of 15% in all categories compared to the traditional concrete production. Such results highlight the importance of using treated plastics to achieve environmental goals and encourages the policymakers to promote the use of treated plastics to achieve environmental goals.
- Statistics show that, on average, nearly 20% of landfills in Nova Scotia are filled with waste plastics. Along with their environmental and financial costs, these plastics can take almost 100 years to decompose. However, the results indicate that the proposed method can utilize all waste plastics in Nova Scotia. Even with the chemicals used in the treatment process, the negative environmental impacts are limited. This incentivizes the use of plastics in the concrete industry rather than the traditional approach of storing and destroying waste plastics.
- Taxes and subsidies stand out as a highly effective financial interventions for regulating activities of supply chain members. Governments possess the capability to oversee the operations of supply chains and impact on their sustainability through financial interventions, such as taxation and subsidization. It is crucial to emphasize the significance of determining the appropriate level of subsidies allocated to green producers and/or the precise amount of taxes levied on the non-green producers to effectively reach sustainability goals. According to the results, if governments impose strict constraints on the producers unwilling to use the treated plastics through imposing higher taxes, and simultaneously incentivize others by offering subsidies, even slightly, the pollution level can be decreased by eliminating non-green producers from the market. For instance, model 2 shows that when the number of concrete producers increases from 7 (representing 63% of the total number of concrete producers in HRM), to 11 the amount of pollution also increases (Table 11).
- Besides governmental interventions, public awareness also plays a crucial role in pushing the concrete producers to adopt greener activities. The impact of increasing public awareness on the use of green concrete is evident when the pollution levels decrease, and it can even contribute to an increase in the profits of producers. As shown previously, accounting for the public awareness and eventually over time, the public will be most inclined to purchase concrete from 63% of the concrete plants in HRM, which have considered using treated plastics. By distributing all concrete plastics among these remaining plants, their profits will increase (Table 10).
- According to the case study, while almost 17,937 tons of plastic per year are sent to landfills in Nova Scotia, nearly 19,000 tons per year of plastics are required to be used in the concrete industry to fill the demand of the construction sector in HRM. This indicates that approximately 1000 tons of plastic per year need to be obtained from other elsewhere. Notably, the proposed framework not only allows for utilization of all plastics produced in Nova Scotia but also require plastics from other places. The significance of this outcome becomes crystal clear when considering the anticipated future growth of population and, consequently, the plastic usage in the area. This trend could further reduce environmental emissions caused by plastics. Given that the policymakers in Nova Scotia have set a target to achieve net zero emissions by 2050 (Halifax Regional Municipality, 2024), the proposed framework can provide effective insights toward achieving this goal.
- Across all strategic settings, market growth consistently increases firms' ability to sustain higher prices. However, the role of customer price sensitivity differs by technology choice. When both firms adopt green technologies, its impact on prices depends on local conditions, whereas in markets dominated by non-green producers, higher price sensitivity clearly constrains pricing. This suggests that green pricing and investment strategies should be tailored to local willingness-to-pay and cost structures, rather than applied uniformly across markets. In markets with partial green adoption, prices tend to move together, meaning that a well-positioned green premium can influence the overall market and even lead non-green competitors to raise prices. To maintain such a premium, firms should combine credible investments in green efforts with clear market signals, such as certification, labeling, and targeted communication. From both managerial and policy perspectives, lowering the effective cost of green production (example, through scale economies, procurement efficiencies, or process improvements) is especially critical in highly price-sensitive markets, where green price premiums are most difficult to sustain.
- From a managerial perspective, the results indicate that incorporating ESG considerations fundamentally reshapes the trade-off between cost and emissions in sustainable concrete production. Beyond environmental improvements driven by greener inputs, the inclusion of governance mechanisms and social influences-such as public awareness and policy interventions-shifts efficient solutions toward lower-emission outcomes while maintaining economic viability. By explicitly accounting for how taxes, subsidies, and public awareness affect producer behavior and market participation over time, the proposed framework captures the role of a

broader set of stakeholders in shaping supply chain decisions. These social and governance factors influence investment choices, coordination across the supply chain, and the adoption of cleaner production practices, thereby pushing the system toward more environmentally efficient configurations without a disproportionate increase in total system cost. This finding highlights that effective ESG integration relies not only on technological solutions, but also on aligning incentives and societal expectations to guide decision-making toward sustainable outcomes.

5. Conclusions

This study evaluated the application of treated plastics in concrete production by reducing cement content up to 3% from environmental, social, and governance (ESG) perspectives through a three-stage approach. First, the environmental impacts were assessed using life cycle assessment (LCA) and SimaPro, showing approximately a 15% reduction in human health, ecosystem, and resource-related impacts. Second, a bi-objective location-allocation model identified the optimal placement of waste treatment centers (WTCs), plastic allocation, and concrete producer capacities, spanning plastic waste suppliers, WTCs, cement plants, and concrete producers, to minimize cost and pollution. Third, an evolutionary game theory (EGT) model examined strategic behavior, where concrete producers choose between “green” (i.e., using treated plastics) and “non-green” (i.e., traditional) production strategies. The model estimated that 63% of producers would adopt green concrete under stable conditions, supported by government interventions. A final revised location-allocation model further optimized long-term profitability for producers adopting treated plastics. Notably, the first stage primarily addressed environmental impacts, while the second and third stages incorporated social, governance, and economic perspectives.

The proposed framework advances the literature by integrating LCA with supply chain optimization and behavioral modeling, offering a holistic tool for sustainable concrete production under policy interventions. The case study in Halifax Regional Municipality (HRM), Canada provides actionable insights for urban decision-making and highlights the practical relevance of ESG principles in industrial applications. Importantly, the results show that ESG integration reshapes the cost-emission trade-off in concrete supply chains by combining environmental measures with governance mechanisms and social influences, such as policy interventions and public awareness. By aligning incentives and stakeholder behavior, the proposed framework shows how cleaner production systems can emerge without undermining economic viability.

To extend the utility of the proposed framework, future studies may consider several enhancements and real-world applications. For example, incorporating uncertainty (e.g., seasonal fluctuations in demand, variable pricing, or disruptions in plastic supply) would improve the robustness of the model under real-world conditions. Employing system dynamics or agent-based simulation could offer additional insight into the time-dependent behavior of sustainable concrete supply chains. From a technical perspective, future studies could investigate how the physical characteristics of plastics (e.g., length, diameter, or aspect ratio) influence their performance in concrete mixtures, and how treatment methods should be optimized accordingly. Moreover, the framework could be adapted to evaluate different types of plastic waste, cement substitutes, or renewable energy sources, offering a more comprehensive analysis of environmental trade-offs. Expanding the case study to other urban regions with distinct regulatory or infrastructural contexts would also improve generalizability. Finally, the integration of the proposed decision-support model with construction management tools could facilitate real-time planning and policy implementation by industry stakeholders, enhancing the framework’s practical value for both public and private sector decision-makers.

In addition to these research directions, certain limitations should be acknowledged. This study is based on LCA simulations of chemically treated PET which requires further assessment of mechanical performance and durability effects. Practical applications may acquire adjustments in mix design or quality control to address potential changes in concrete properties. Likewise, although treatment and transport costs were modeled, real-world adoption could also depend on factors such as treatment expenses, energy use, and market price premiums. These aspects represent important areas for future empirical research to complement these simulation-based findings.

CRediT authorship contribution statement

Ali Mahmoudi: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization; **Hamid Afshari:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization; **Hassan Sarhadi:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization; **Armin Jabbarzadeh:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Data availability

Data will be made available on request.

Declaration of competing interest

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Appendix A. Augmented ϵ-constraint

For solving multi-objective problems, the following mathematical formulations should be addressed:

$$\min_{x, s_2, \dots, s_p} \quad f_1(x) - \lambda\left(\frac{s_2}{r_2} + \frac{s_3}{r_3} + \dots + \frac{s_p}{r_p}\right)$$

$$\text{s.t.} \quad \begin{cases} f_2(x) + s_2 & = \epsilon_2 \\ f_3(x) + s_3 & = \epsilon_3 \\ f_4(x) + s_4 & = \epsilon_4 \\ \vdots & \quad \vdots \\ f_p(x) + s_p & = \epsilon_p \\ s_1, \dots, s_p & \in \mathbb{R}^+ \\ x & \in \Omega \end{cases} \tag{A.1}$$

In Eq. (A.1), the parameters $\epsilon_2, \epsilon_3, \dots, \epsilon_p$ correspond to the values on the right-hand side for the specific iteration, selected from the grid points associated with objective functions $2, 3, \dots, p$. Similarly, the parameters $r_2, r_3, \dots, r_p$ denote the ranges of the respective objective functions as determined from the payoff table. The variables $s_2, s_3, \dots, s_p$ represent the surplus variables pertaining to the corresponding constraints. Additionally, λ is a sufficiently small value $\lambda \in [10^{-6}, 10^{-3}]$ utilized within the formulation. Ω symbolizes the feasible region of the primary problem (Mavrotas, 2009).

Appendix B. Evolutionary game theory

Proof B.1. (Proof of Lemma 1)

To establish the equilibrium pricing results in Lemma 1, we first verify the concavity of the profit function with respect to the decision variable. The second derivative of the profit function for the first concrete producer in the green-green scenario is:

$$\frac{\partial^2 \pi_{g,g}}{\partial p_{g,g}^2} = -2\rho < 0 \tag{B.1}$$

This confirms that the profit function is strictly concave in $p_{v,r}$, ensuring a unique optimal price.Next, define the following constants used in the pricing expressions:

$$A_1 = (2\rho - \sigma)(w_{v,r}\lambda_1 - w_{r,v}\lambda_2)$$

$$A_2 = (2\rho + \sigma)$$

$$A_3 = \frac{(-2\rho + \sigma)^2(w_{v,r}\lambda_1 - w_{r,v}\lambda_2)}{(2\rho + \sigma)^2}$$

To obtain the Nash equilibrium prices, we set the first-order conditions of the profit functions with respect to $p_{v,r}$ and $p_{r,v}$ equal to zero, which yields the following system:

$$\begin{cases} \dfrac{\partial^2 \pi_{v,r}}{\partial p_{v,r}^2} = \varphi - \rho p_{v,r} - \rho(-c + S + p_{v,r}) + \sigma p_{r,v} + w_{v,r}\lambda_1 - w_{r,v}\lambda_2 = 0 \\ \dfrac{\partial^2 \pi_{r,v}}{\partial p_{v,r}^2} = \varphi + \sigma p_{v,r} - \rho p_{r,v} - \rho(-c + S + p_{r,v}) - w_{v,r}\lambda_1 + w_{r,v}\lambda_2 = 0 \end{cases} \tag{B.2}$$

Solving this system leads directly to the equilibrium prices reported in Lemma 1.

Proof B.2.

$$\frac{dp_{v,r}^*}{d\varphi} = \frac{1}{2\rho - \sigma} > 0 \Rightarrow \begin{cases} \varphi < \dfrac{S\sigma}{2} - A_3 \\ 0 < c < \dfrac{S\sigma - 2\varphi - 2A_3}{\sigma} \end{cases} \tag{B.3}$$

$$\frac{dp^*_{v,r}}{d\rho} < 0 \Rightarrow \begin{cases} \varphi \leq \dfrac{S\sigma}{2} - A_3 \\ c > \dfrac{S\sigma - 2\varphi - 2A_3}{\sigma} \end{cases} \tag{B.4}$$

$$\frac{d\pi^*_{v,r}}{d\varphi} = \frac{2\rho(2\rho+\sigma)\big((2\rho+\sigma)(-((c-S)(\rho-\sigma))+\varphi)+(2\rho-\sigma)w_{v,r}\lambda_1+(-2\rho+\sigma)w_{r,v}\lambda_2\big)}{(-4\rho^2+\sigma^2)^2}$$
$$\begin{cases} >0 \quad if \quad \varphi > \frac{(c-S)(\rho-\sigma)(2\rho+\sigma)+(-2\rho+\sigma)w_{v,r}\lambda_1+(2\rho-\sigma)w_{r,v}\lambda_2}{2\rho+\sigma} \\ <0 \quad if \quad \begin{cases} \varphi > \frac{S(-2\rho^2+\rho\sigma+\sigma^2)+(-2\rho+\sigma)w_{v,r}\lambda_1+(2\rho-\sigma)w_{r,v}\lambda_2}{2\rho+\sigma} \\ \text{and} \\ c > \frac{(2\rho+\sigma)(S(\rho-\sigma)+\varphi)+(2\rho-\sigma)(w_{v,r}\lambda_1-w_{r,v}\lambda_2)}{(\rho-\sigma)(2\rho+\sigma)} \end{cases} \end{cases} \tag{B.5}$$

$$\frac{d\pi^*_{v,r}}{d\rho} = \frac{\left(\begin{smallmatrix}(2\rho+\sigma)((c-S)(\rho-\sigma)-\varphi) \\ +(-2\rho+\sigma)w_{v,r}\lambda_1+(2\rho-\sigma)w_{r,v}\lambda_2\end{smallmatrix}\right)\left(\begin{smallmatrix}(2\rho+\sigma)^2\left(\begin{smallmatrix}(c-S)\left(2\rho^2-\rho\sigma+\sigma^2\right) \\ +(2\rho+\sigma)\varphi\end{smallmatrix}\right) \\ +(2\rho-\sigma)^3\left(w_{v,r}\lambda_1-w_{r,v}\lambda_2\right)\end{smallmatrix}\right)}{\left(4\rho^2-\sigma^2\right)^3}$$
$$\begin{cases} >0 \ \to \begin{cases} 0 < w_{r,v} < \frac{w_{v,r}\lambda_1}{\lambda_2} \\ \text{and} \quad \varphi < -\frac{(2\rho-\sigma)(w_{v,r}\lambda_1-w_{r,v}\lambda_2)}{(2\rho+\sigma)} \\ \text{and} \quad S > -\frac{(2\rho+\sigma)\varphi+(-2\rho+\sigma)w_{v,r}\lambda_1+(2\rho-\sigma)w_{r,v}\lambda_2}{(\rho-\sigma)(2\rho+\sigma)} \\ \text{and} \quad c < \frac{(2\rho+\sigma)(S(\rho-\sigma)+\varphi)+(2\rho-\sigma)(w_{v,r}\lambda_1-w_{r,v}\lambda_2)}{(\rho-\sigma)(2\rho+\sigma)} \end{cases} \\ <0 \ \to \begin{cases} 0 < w_{r,v} < \frac{w_{v,r}\lambda_1}{\lambda_2} \\ \text{and} \quad \varphi < -\frac{(2\rho-\sigma)(w_{v,r}\lambda_1-w_{r,v}\lambda_2)}{(2\rho+\sigma)} \\ \text{and} \quad S \leq -\frac{(2\rho+\sigma)\varphi+(-2\rho+\sigma)w_{v,r}\lambda_1+(2\rho-\sigma)w_{r,v}\lambda_2}{(\rho-\sigma)(2\rho+\sigma)} \\ \text{and} \quad c < \frac{\left((2\rho+\sigma)^2\left(S(2\rho^2-\rho\sigma+\sigma^2)-(2\rho+\sigma)\varphi\right)-(2\rho-\sigma)^3(w_{v,r}\lambda_1-w_{r,v}\lambda_2)\right)}{(2\rho+\sigma)^2(2\rho^2-\rho\sigma+\sigma^2)} \end{cases} \end{cases} \tag{B.6}$$

$$\frac{d\pi^*_{v,r}}{dc} = \frac{2\rho(-\rho+\sigma)(2\rho+\sigma)\big((2\rho+\sigma)(-((c-S)(\rho-\sigma))+\varphi)+(2\rho-\sigma)w_{v,r}\lambda_1+(-2\rho+\sigma)w_{r,v}\lambda_2\big)}{(-4\rho^2+\sigma^2)^2}$$
$$\begin{cases} >0 \quad \to c < \frac{(2\rho+\sigma)(S(\rho-\sigma)+\varphi)+(2\rho-\sigma)(w_{v,r}\lambda_1-w_{r,v}\lambda_2)}{(\rho-\sigma)(2\rho+\sigma)} \\ <0 \quad \to S > \frac{(2\rho+\sigma)(c\rho-c\sigma-\varphi)+(-2\rho+\sigma)w_{v,r}\lambda_1+(2\rho-\sigma)w_{r,v}\lambda_2}{(\rho-\sigma)(2\rho+\sigma)} \end{cases} \tag{B.7}$$

Proof B.3. (Proof of Lemma 2)

To establish the equilibrium pricing results in Lemma 2, we first verify the concavity of the profit functions with respect to their decision variables. For the green and non-green producers in the second strategy profile, the second derivatives of the profit functions are

$$\frac{\partial^2\pi_{v,r}}{\partial p^2_{v,r}} = -2\rho \leq 0, \qquad \frac{\partial^2\pi_{r,v}}{\partial p^2_{r,v}} = -2\rho \leq 0, \tag{B.8}$$

confirming that both functions are strictly concave in their respective prices.

The following constants are used in the pricing expressions:

$$B_1 = 2\rho\varphi + \sigma\varphi + w_{r,v}(\sigma\lambda_1 - 2\rho\lambda_2),$$
$$B_2 = w_{r,v}(-\sigma\lambda_1 + 2\rho\lambda_2),$$
$$B_3 = w_{r,v}(-2\sigma\lambda_1 + \rho\lambda_2),$$
$$B_4 = w_{r,v}\left[-2(4\rho^3 + 3\rho\sigma^2)\lambda_1 + \sigma(12\rho^2 + \sigma^2)\lambda_2\right].$$

To obtain the Nash equilibrium prices, we set the first-order conditions of the profit functions with respect to $p_{v,r}$ and $p_{r,v}$:

$$\begin{cases} \dfrac{\partial\pi_{v,r}}{\partial p_{v,r}} = \varphi - \rho p_{v,r} - \rho(-c - T + p_{v,r}) + \sigma p_{r,v} - w_{r,v}\lambda_2 = 0, \\ \dfrac{\partial\pi_{r,v}}{\partial p_{r,v}} = \varphi + \sigma p_{v,r} - \rho p_{r,v} - \rho(-c + S + p_{r,v}) + w_{r,v}\lambda_1 = 0. \end{cases} \tag{B.9}$$

Solving this system yields the equilibrium prices reported in Lemma 2.

Proof B.4. (Proof of Lemma 3)

To verify the uniqueness of the optimal price, we first examine the concavity of the profit function in the non-green scenario. The second derivative of the profit function with respect to its decision variable is

$$\frac{\partial^2 \pi_{(v,r)}}{\partial p_{(v,r)}^2} = -2\rho \le 0, \tag{B.10}$$

indicating that the profit function is strictly concave in price.

To obtain the Nash equilibrium prices for the two non-green producers, we set the first-order conditions with respect to $p_{(v,r)}$ and $p_{(r,v)}$:

$$\begin{cases} \frac{\partial \pi_{(v,r)}}{\partial p_{(v,r)}} = (c+T)\rho + \varphi - 2\rho\, p_{(v,r)} + \sigma\, p_{(r,v)} = 0, \\ \frac{\partial \pi_{(r,v)}}{\partial p_{(r,v)}} = (c+T)\rho + \varphi + \sigma\, p_{(v,r)} - 2\rho\, p_{(r,v)} = 0. \end{cases} \tag{B.11}$$

Solving this system yields the optimal price reported in Lemma 3.

The following relationships exist between the optimal profit and quantity level of concrete producers and certain parameters.

$$\frac{d\pi^*_{v,r}}{d\varphi} = \frac{2\rho(-2T\rho^2 - S\rho\sigma + T\sigma^2 + c(-2\rho^2 + \rho\sigma + \sigma^2) + B_1)}{(-2\rho+\sigma)^2(2\rho+\sigma)}$$
$$\begin{cases} > 0 \quad \to \varphi > \frac{2T\rho^2+S\rho\sigma-T\sigma^2+B_2}{2\rho+\sigma} \quad \text{and} \quad 0 < c < \frac{-S\rho\sigma+T(-2\rho^2+\sigma^2)+B_1}{(\rho-\sigma)(2\rho+\sigma)} \\ < 0 \quad \to \varphi \le \frac{2T\rho^2+S\rho\sigma-T\sigma^2+B_2}{2\rho+\sigma} \end{cases} \tag{B.12}$$

$$\frac{d\pi^*_{v,r}}{d\rho} = \frac{1}{(4\rho^2-\sigma^2)^3}\left(2T\rho^2 + S\rho\sigma - T\sigma^2 + c(\rho-\sigma)(2\rho+\sigma) - (2\rho+\sigma)\varphi + w_{r,v}(-\sigma\lambda_1 + 2\rho\lambda_2)\right)$$
$$\begin{cases} > 0 \quad \to \begin{cases} \varphi > \frac{2T\rho^2+S\rho\sigma-T\sigma^2+B_2}{2\rho+\sigma} \\ c > \frac{-S\rho\sigma+T(-2\rho^2+\sigma^2)+B_1}{(\rho-\sigma)(2\rho+\sigma)} \end{cases} \\ < 0 \quad \to \begin{cases} \varphi \le \frac{2T\rho^2+S\rho\sigma-T\sigma^2+B_2}{2\rho+\sigma} \\ c < \frac{-S\rho\sigma+T(-2\rho^2+\sigma^2)+B_1}{(\rho-\sigma)(2\rho+\sigma)} \end{cases} \end{cases} \tag{B.13}$$

$$\frac{d\pi^*_{r,v}}{d\varphi} = \frac{2\rho\left(2S\rho^2 + T\rho\sigma - S\sigma^2 + c\left(-2\rho^2 + \rho\sigma + \sigma^2\right) + 2\rho\varphi + \sigma\varphi + w_{r,v}\left(2\rho\lambda_1 - \sigma\lambda_2\right)\right)}{(-2\rho+\sigma)^2(2\rho+\sigma)}$$
$$\begin{cases} > 0 \quad \to \begin{cases} \varphi < c(\rho-\sigma) + \frac{B_3}{2\rho+\sigma} \\ 0 < T \le \frac{(2\rho+\sigma)(c(\rho-\sigma)-\varphi)+B_3}{\rho\sigma} \\ S > \frac{-T\rho\sigma+c(\rho-\sigma)(2\rho+\sigma)-(2\rho+\sigma)\varphi+B_3}{2\rho^2-\sigma^2} \end{cases} \\ < 0 \quad \to \varphi \le \frac{2(c-S)\rho^2-(c+T)\rho\sigma+(-c+S)\sigma^2+B_3}{2\rho+\sigma} \end{cases} \tag{B.14}$$

$$\frac{d\pi^*}{d\rho}=\frac{\begin{pmatrix}\big(-2S\rho^2-T\rho\sigma+S\sigma^2+c(\rho-\sigma)(2\rho+\sigma)-(2\rho+\sigma)\varphi+w_{r,v}\big(-2\rho\lambda_1+\sigma\lambda_2\big)\big)\\ \big(c(2\rho+\sigma)^2\big(2\rho^2-\rho\sigma+\sigma^2\big)+T\rho\sigma\big(4\rho^2+3\sigma^2\big)-S\big(8\rho^4+2\rho^2\sigma^2+\sigma^4\big)\\ +(2\rho+\sigma)^3\varphi+w_{r,v}\big(\big(8\rho^3+6\rho\sigma^2\big)\lambda_1-\sigma\big(12\rho^2+\sigma^2\big)\lambda_2\big)\big)\end{pmatrix}}{\big(4\rho^2-\sigma^2\big)^3}$$

$$\begin{cases}>0\rightarrow\begin{cases}c>\frac{4S\rho^2+4S\rho\sigma+(2S+T)\sigma^2+2\sigma w_{r,v}\left(\lambda_1+\lambda_2\right)}{(2\rho+\sigma)^2}\\ \text{and}\\ \frac{8(-c+S)\rho^4-4(c+T)\rho^3\sigma+2(-c+S)\rho^2\sigma^2}{-3(c+T)\rho\sigma^3+(-c+S)\sigma^4+B_4}<\varphi\\ \text{and}\\ \varphi<\frac{2(c-S)\rho^2-(c+T)\rho\sigma+(-c+S)\sigma^2+B_3}{2\rho+\sigma}\end{cases}\\ <0\rightarrow\begin{cases}2\rho\frac{2(c-S)\rho^2-(c+T)\rho\sigma+(-c+S)\sigma^2+B_3}{2\rho+\sigma}\\ \text{and}\\ 0<c<\frac{4S\rho^2+4S\rho\sigma+(2S+T)\sigma^2+2\sigma w_{r,v}\left(\lambda_1+\lambda_2\right)}{(2\rho+\sigma)^2}\end{cases}\end{cases} \tag{B.15}$$

$$\frac{dQ^*_{v,r}}{dw_{r,v}}=\frac{\rho(\sigma\lambda_1-2\rho\lambda_2)}{4\rho^2-\sigma^2}$$

$$\begin{cases}>0\quad\rightarrow\left(\frac{2\rho\lambda_2}{\lambda_1}<\sigma<\rho\quad\text{and}\quad 0<\lambda_2<\frac{\lambda_1}{2}\right)\\ <0\quad\rightarrow\left(0<\lambda_2<\frac{\lambda_1}{2}\quad\text{and}\quad\rho>\lambda_1\quad\text{and}\quad 0<\sigma<\frac{2\rho\lambda_2}{\lambda_1}\right)\end{cases} \tag{B.16}$$

$$\frac{dQ^*_{(r,v)}}{dw_{(r,v)}}=\frac{\rho(-2\rho\lambda_1+\sigma\lambda_2)}{(-4\rho^2+\sigma^2)}$$

$$\begin{cases}>0\quad\rightarrow\quad\lambda_2>2\lambda_1\quad\text{and}\quad\rho>\lambda_2\quad\text{and}\quad 0<\sigma<\frac{2\rho\lambda_1}{\lambda_2}\\ <0\quad\rightarrow\quad\frac{2\rho\lambda_1}{\lambda_2}<\sigma\end{cases} \tag{B.17}$$

Proof B.5. Based on Proposition 6, following sensitivity analysis can be conducted for the third strategy profile.

$$\frac{dp^*_{v,r}}{d\varphi}=\frac{1}{2\rho-\sigma}>0 \tag{B.18}$$

$$\frac{dp^*_{v,r}}{d\rho}=\frac{(c+T)\sigma+2\varphi}{(-2\rho+\sigma)^2}>0 \tag{B.19}$$

$$\frac{dp^*_{v,r}}{d\sigma}=\frac{(c+T)\rho+\varphi}{(-2\rho+\sigma)^2}>0 \tag{B.20}$$

$$\frac{dp^*_{v,r}}{dc}=\frac{\rho}{2\rho-\sigma} \tag{B.21}$$

$$\frac{d\pi^*_{v,r}}{d\varphi}=\frac{2\rho(-((c+T)(\rho-\sigma))+\varphi)}{(-2\rho+\sigma)^2}\begin{cases}>0\quad\rightarrow\quad T<-c+\frac{\varphi}{\rho-\sigma}\\ <0\quad\rightarrow\quad T>-c+\frac{\varphi}{\rho-\sigma}\end{cases} \tag{B.22}$$

$$\frac{d\pi^*_{v,r}}{d\rho}=\frac{(c+T)^2(\rho-\sigma)\left(\varphi^2-\rho\sigma+\sigma^2\right)-2(c+T)\sigma\varphi-(2\rho+\sigma)\varphi^2}{(2\rho-\sigma)^3}$$

$$\begin{cases}>0\quad\rightarrow\quad T\le -c-\frac{(2\rho+\sigma)\varphi}{2\rho^2-\rho\sigma+\sigma^2}\quad\text{or}\quad T>-c+\frac{\varphi}{\rho-\sigma}\\ <0\quad\rightarrow\quad -c-\frac{(2\rho+\sigma)\varphi}{2\rho^2-\rho\sigma-\sigma^2}<T<-c+\frac{\varphi}{\rho-\sigma}\end{cases} \tag{B.23}$$

$$\frac{d\pi^*_{v,r}}{d\sigma}=\frac{2\rho\left(-(c+T)^2\rho(\rho-\sigma)+(c+T)\sigma\varphi+\varphi^2\right)}{(2\rho-\sigma)^3} \tag{B.24}$$

$$\begin{cases} > 0 & \rightarrow \quad -\dfrac{c\rho + \varphi}{\rho} < T < -c + \dfrac{\varphi}{\rho - \sigma} \\ < 0 & \rightarrow \quad T < -\dfrac{c\rho + \varphi}{\rho} \quad \text{or} \quad T > -c + \dfrac{\varphi}{\rho - \sigma} \end{cases}$$

$$\frac{d\pi^*_{v,r}}{dc} = \frac{2\rho(\rho - \sigma)((c + T)(\rho - \sigma) - \varphi)}{(-2\rho + \sigma)^2} \tag{B.25}$$

$$\begin{cases} > 0 & \rightarrow \quad T > \dfrac{-c\rho + c\sigma + \varphi}{\rho - \sigma} \\ < 0 & \rightarrow \quad T < \dfrac{-c\rho + c\sigma + \varphi}{\rho - \sigma} \end{cases}$$

Appendix C. Extra details

The table below introduces the list of locations considered for plastic suppliers, cement, and concrete producers.

Table C.1
Facility names and locations.

#	Name of Facilities	Type	Location
1	Lafarge Canada	Cement Plant	Brookfield, Nova Scotia
2	V J Rice Concrete Limited	Concrete Producer	Mount Uniacke, Halifax, Nova Scotia
3	Sackville Concrete	Concrete Producer	Lower Sackville, Nova Scotia
4	Casey Concrete	Concrete Producer	Bedford, Nova Scotia
5	Quality Concrete	Concrete Producer	Bedford, Nova Scotia
6	Bedford Ready Mix	Concrete Producer	Bedford, Nova Scotia
7	Quality Concrete	Concrete Producer	Dartmouth, Nova Scotia
8	Quality Concrete	Concrete Producer	Halifax, Nova Scotia
9	Inspired Concrete	Concrete Producer	Halifax, Nova Scotia
10	East Coast Foundations	Concrete Producer	Dartmouth, Nova Scotia
11	J&R Concrete	Concrete Producer	Westphal, Nova Scotia
12	Moore & Cormier Contracting	Concrete Producer	Dartmouth, Nova Scotia
13	Polymershapes	Manufacturer	Dartmouth, Nova Scotia
14	Concept Plastics	Manufacturer	Dartmouth, Nova Scotia
15	EM Plastics & Electric Products Ltd.	Manufacturer	Dartmouth, Nova Scotia
16	Neocon International	Manufacturer	Dartmouth, Nova Scotia
17	Otter Lake Landfill (OLL)	Landfill	Otter Lake, Nova Scotia
18	Western Management Center (WMC)	Landfill	Chester Basin, Nova Scotia
19	Kaizer Meadow Landfill (KML)	Landfill	Chester, Nova Scotia
20	West Hants Landfill (WHL)	Landfill	Centre Burlington, Nova Scotia
21	Eastern Hants Waste Management Center (EHWMC)	Landfill	Hants County, Nova Scotia
22	Sheet Harbour Dump (SHD)	Landfill	Sheet Harbour, Nova Scotia
23	Colchester Balefill & Composting Facility (CBCF)	Landfill	Kemptown, Nova Scotia
24	Antigonish Landfill (AL)	Landfill	Antigonish, Nova Scotia
25	Pictou County Solid Waste (PCSW)	Landfill	Mount William, Nova Scotia
26	Little Forks Municipal Landfill (LFML)	Landfill	Chignecto, Nova Scotia
27	Eco360 Waste Management Facility (EWMF)	Landfill	Berry Mills, New Brunswick
28	AIM Recycling Atlantic	Landfill	Saint John, New Brunswick
29	Kings Regional Service Commission (KRSC)	Landfill	Sussex, New Brunswick

Also, the values considered for the parameters in the evolutionary game theory approach are presented in Table C.2. Table C.3 shows the value of the optimal solution in each iteration of the augmented ϵ-constraints algorithm.

Table C.2
Parameter values in the evolutionary game theory.

Parameter	Value
c	0.024 \$/kg
(w_1, w_2)	(40, 50)
ϕ	896,850,000 kg
(λ_1, λ_2)	(1.1, 0.6)
(ρ, σ)	(1, 0.2)
k	0.35

Table C.3
Results of the Pareto-optimal solutions.

No. Solution	First Objective Function	Second Objective Function
1	37,561,639	7,202,253.473
2	37,512,551	7,211,146.205
3	37,491,450	7,216,475.538
4	37,445,409	7,224,400.451
5	37,439,344	7,231,112.652
6	37,385,773	7,238,077.053
7	37,380,735	7,240,251.362
8	37,370,587	7,249,419.819
9	37,360,468	7,255,571.268
10	37,351,571	7,264,772.742

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