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A mathematical optimization model for sustainable product line design and pricing under regulatory incentives[☆]

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ABSTRACT

As sustainability concerns increasingly influence product line decisions and regulatory incentives, firms must adopt optimization strategies that accommodate diverse consumer segments with varying levels of environmental awareness and willingness-to-pay while designing cost-effective yet sustainable product offerings that may benefit from sustainability incentives. To address these challenges, this study develops a mathematical optimization model that captures the strategic interactions between firms, consumers, and regulatory agencies by integrating market heterogeneity, environmental awareness, and regulatory incentives. We begin by constructing and experimentally validating a utility-based consumer choice model that reflects differences in environmental awareness and willingness-to-pay. This consumer behavior framework is then integrated with regulatory incentives to address the challenges of product line design and pricing for firms offering both conventional and environmentally friendly products. Our model builds on previous research on optimal product line expansion by analyzing the interplay between consumer preferences, use-phase efficiency, and regulatory incentives. Through computational analyses, we demonstrate how factors such as market segmentation, manufacturing costs, and incentives shape optimal product design, pricing strategies, and environmental impact. The findings provide actionable insights for policymakers, helping them design regulatory incentives that effectively encourage firms to balance profitability with environmental responsibility.

1. Introduction

Our planet's delicately balanced ecosystem is under stress due to rapid economic growth fueled by excessive consumption. To address the increasing sustainability concerns, companies develop strategies or novel business models to minimize the environmental impact of their activities. In this context, the inclusion of environment-friendly or "green" products in the product line is a commonly observed strategy. Green products are designed to have a smaller carbon footprint than their traditional counterparts in terms of raw material supply and use, energy consumption, recycling, and waste management processes.

Due to growing sustainability concerns, some consumer segments now consider a product's environmental impact as a key selection criterion, in addition to traditional factors such as price. This behavioral shift has increased the demand for green products [1]. The key factors influencing the purchase, use, and disposal of environmentally-friendly products are consumer environmental awareness and concerns [2], perceived value, product pricing, and government policies and incentives aimed at encouraging the adoption of "green products" and regulating end-of-life disposal and recycling practices. The compounding effects of these drivers create a heterogeneous market characterized by segments that variably respond to green products.

The incorporation of green products into the product assortments of firms serving various retail sectors signals a notable shift towards greater environmental consciousness. For instance, alongside traditional laundry detergents, ultra-concentrated detergents have rapidly established a presence in retail outlets. However, ultra-concentrated laundry detergents, which aim to use natural resources more sustainably and reduce the environmental footprint of the laundry process, may fall short of achieving the intended results in environmental performance — even generate increased greenhouse gas emissions — if consumers do not adhere to the prescribed dosages or water temperatures [3,4]. Consequently, an analysis that overlooks variations in consumer behavior during the use phase of green products will not effectively support a firm's product line, pricing, and product design strategies and, for the regulatory agency, will not result in effective incentive design schemes.

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The goal of this study is to investigate the impact of market heterogeneity on product line design and pricing, the role of regulatory incentives in shaping green product development, and how consumer usage patterns influence both green product design decisions and regulatory incentive structures. Specifically, this paper studies a firm's product line design and pricing problems. The firm operates in a heterogeneous market where customer segments' product valuations and sensitivity to products' environmental impacts vary. An analytical framework utilizing a stylized model is developed to investigate the interplay between market heterogeneity, green product design decisions, and regulatory interventions. The hypothesis of a "heterogeneous market" is empirically tested through an experiment. The model incorporates a rational consumer response framework, which accounts for market heterogeneity, into the firm's product line design and pricing decisions. The model is further expanded by integrating regulatory mechanisms governments can institute to achieve their intended sustainability goals. The paper also presents a discussion of the consumers' use-phase behavior when using green products. In consideration of the size of the retail industry, it is evident that such a discussion can bring about value not just in the context of effective product design and pricing policies, but also in the management of the environmental value chain.

This study aims to provide insights for firms and regulatory agencies on aligning operational decisions with emission reduction targets. It specifically examines consumer behavior during the use phase, with a focus on products that have a relatively higher use-phase environmental impact [5] and detergents [3,6]. Key questions include: (1) How does market heterogeneity influence product line design and pricing strategies? (2) What is the role of regulatory incentives in shaping green product design decisions? (3) How does consumer use-phase behavior impact the green product design decisions and regulatory agencies' incentive schemes?

The design of product lines with green products presents a unique challenge for firms as they must balance consumer preferences, cost structures, and regulatory constraints. Research in this area has largely focused on optimizing product line decisions by considering consumer heterogeneity, pricing strategies, and competitive market dynamics. However, significant gaps remain in understanding the interplay between regulatory incentives and real-world consumer behavior, which this study aims to address.

The paper makes several key contributions to the intersection of operations management and marketing by addressing the complex optimization of sustainable product line design and pricing decisions. It introduces a novel, integrated mathematical model that incorporates both standard and green products as substitutes, while capturing the critical role of consumer behavior in the use phase of green products—an aspect often overlooked in existing research. Additionally, the paper integrates regulatory mechanisms, specifically incentives for green products, into the decision-making process, providing insights into how regulatory interventions can shape firms' product offerings, pricing strategies, and overall environmental performance. Through computational analyses, the study highlights how market heterogeneity, environmental awareness, and use-phase efficiencies drive optimal product line designs and regulatory incentives.

While individual elements of our model, such as consumer heterogeneity, convex greening costs, regulatory incentives, and demand responses, have been studied in isolation, this paper contributes by demonstrating how their joint interaction generates policy and design insights that cannot be obtained from any single component alone. In particular, the integrated framework enables regulatory agencies to quantify the magnitude of rebound effects, identify how different consumer segments contribute to emissions outcomes, and determine incentive levels that are consistent with targeted emissions reductions once firm responses and use-phase behavior are explicitly incorporated. This integrated approach helps lay the foundation for developing a framework that can provide guidance to firms seeking to improve their sustainability impact while staying competitive in various markets, as well as to regulatory agencies aiming to use their resources more efficiently.

In the subsequent sections, this study provides a comprehensive analysis of the factors influencing product line design and pricing strategies for green products. Section 2 offers a detailed literature review, focusing on the design of green products and consumer behavior in the use phase. Section 2.1 reviews various studies that examine the effects of consumer segments, market structures, recycled materials, pricing strategies, and government policies on the design and pricing of green products. Section 2.2 explores sustainable consumer behavior and highlights the importance of consumer environmental awareness in green product purchase and use. Section 2.3 explores the role of regulatory agencies in introducing incentives or penalties to guide firms toward achieving environmental targets. Section 3 introduces a model incorporating consumer preferences and regulatory incentives, which is further analyzed in Section 4 through experimental validation to examine how consumers' Willingness-to-Pay (WtP) changes with environmental awareness. Section 5 addresses the manufacturer's optimization problem, incorporating regulatory incentives. Section 6 discusses the incentive design problem in the context regulatory incentives and from the perspective of the regulatory agency. Section 7 presents a computational analysis to evaluate a multitude of scenarios, highlighting the impact of environmental awareness, segment sizes, use-phase efficiencies, and manufacturing costs on product design and pricing decisions, and regulatory strategies. Finally, Section 8 concludes with insights on the policy implications and potential extensions of the model.

2. Literature review

Section 2 provides a comprehensive literature review on sustainable product line design, consumer behavior, and regulatory incentives. Section 2.1 examines prior research on green product design, focusing on factors such as consumer preference heterogeneity, cost structures, and market dynamics. Section 2.2 explores consumer attitudes and behaviors toward green products, emphasizing the impact of consumer environmental awareness. Finally, Section 2.3 discusses the role of regulatory agencies in shaping sustainable product markets through incentives and penalties, analyzing how policy interventions influence firms' pricing and design strategies. We also note that the contribution of this study does not lie in introducing a new behavioral or cost assumption in isolation, but in showing how their interaction shapes incentive calibration and emissions outcomes in equilibrium.

2.1. Design of Green products

Firms must consider multiple factors when designing green products. These include consumer preference heterogeneity and the nonlinear relationship between production costs and quality levels.

Research on product line and pricing problems often assumes a product line with two distinct products: a conventional product and a green product designed with environmental concerns. Chen [7] examines product line strategies, considering environmentally sensitive and insensitive consumers; using an analytical model, the study investigates how green products can enhance the firm's bottom line.

Yenipazarli and Vakharia [8] analyze the product line and pricing problem in the presence of limited green product development capacity. By examining the interplay between operational decisions and existing capacity, they find that a two-level pricing structure, when capacity is sufficient, mitigates the cannibalization effect between brown and green products.

Yenipazarli and Vakharia [9] study a problem in a setting similar to Yenipazarli and Vakharia [8] and investigate the conditions under which the presence of green products enhances the firm's bottom line and simultaneously reduces its environmental footprint. They find that both goals are achievable as long as the firm thoroughly understands its consumers' sensitivity to green and brown attributes in a product.

Lin et al. [10] focus on a firm that makes coproducts (i.e., products at different quality levels) using materials that would otherwise be discarded and study the firm's optimal quality and price decisions of its coproduction. They find that if the market comprises a significant group of environmentally conscious consumers, the firm should leverage the environmental value when positioning the green product, even if it means not fully satisfying the demand of some conventional consumers.

Shen et al. [11] investigate how product differentiation in terms of quality influences competition between green and non-green products. They develop a price and quality-driven consumer choice model and demonstrate that when green products, perceived as higher quality, compete with non-green alternatives, improving product quality enhances consumer welfare while simultaneously reducing environmental impact.

A recent study closely related to our research is Liu [12], which examines the introduction and pricing of green products in the presence of network externalities. The study also explores how factors such as consumer education influence the adoption of green products. Table 1 in [12] highlights key characteristics of their problem, contributing to the growing literature on green products in operations management. Liu [12] provides valuable insights into leveraging network effects and consumer awareness to drive green product adoption. Our study builds on and extends these insights in several ways: Our research examines green product quality, pricing, and introduction in the context of regulatory incentives. We incorporate a regulatory incentive mechanism designed to achieve specific environmental targets, analyzing how policy interventions shape firm decisions and influence sustainability outcomes. We take a multidisciplinary approach by experimentally validating the relationship between a product's greenness level and consumer willingness-to-pay. These empirical insights are then integrated into our optimization framework, enhancing the practical applicability of our model. Our study also considers a market where consumers differ in both product valuation and use-phase behavior. This allows us to explore how variability in consumer behavior affects green product strategies, offering a more comprehensive perspective on sustainable product design. By combining analytical modeling, experimental validation, and regulatory considerations, our study complements the findings of Liu [12] while offering additional insights for firms and policymakers navigating the trade-offs between profitability and environmental impact.

Several studies further explore the challenges of product line design and pricing, considering various market conditions and regulatory factors. Chen and Liu [13] study competitive product design and pricing decisions in a duopoly setting where the market includes environmentally conscious and non-environmental consumers. They conclude that the quality level of the standard product sets a standard for the pricing of the other products in the market, regardless of the product type. Cohen et al. [14] address the competing firms' product line and pricing problems. They demonstrate that although government R&D and sales subsidies incentivize firms to produce greener products, the total environmental impact is unclear: R&D subsidies can have unpredictable negative environmental impacts, while sales subsidies may result in overall environmental benefits.

Moreover, there exist studies that examine product line design and pricing problems through the lens of channel coordination. Basiri and Heydari [15] consider a setting where the retailer determines the retail price and sales effort level for the green product, while the manufacturer is responsible for deciding the quality of the green product. They numerically demonstrate that the supply chain's profit reaches its highest potential with collaboration. Also, Ranjan and Jha [16] focus on a supply chain comprising a single manufacturer and retailer that offers both standard and green products. Their findings indicate that environmentally favorable outcomes emerge when the two players collaborate.

Lastly, we visit studies investigating the impact of regulatory mechanisms on the design of green products. Hafezi and Zolfagharinia [17] demonstrate that government regulations should consider the cost of green product development, the proportion of environmentally conscious consumers in the market, and consumers' WtP for green products. They also conclude that under stringent regulations, firms might choose not to invest in green product innovation, opting instead to produce only conventional products. Ghosh et al. [18] examine the issue of determining the optimal environmental quality level and pricing of green products under government regulations in a duopoly setting. Their findings indicate that when government penalties or subsidies are relatively low, a firm with lower greening costs than its competitor tends to produce products with higher environmental friendliness.

The scope of this literature stream has been expanded through studies that integrate various dimensions and focus on different frameworks, including diverse market leadership scenarios [19], different subsidy mechanisms [20], various environmental tax schemes [21], social welfare considerations in a duopoly setting [22], government's subsidy scheme [23], green product decisions in competitive contexts with carbon emission trading [24], government green publicity and emission tax policies [25], circular economy [26], remanufacturing [27], and supply chain contracts [28].

This paper builds on the reviewed literature by presenting a comprehensive framework that integrates firm-level product line design and pricing decisions, and regulatory interventions. It connects firms' product design and pricing strategies with consumer behavior during the use phase and the incentive design scheme of the regulatory agency. By incorporating market segmentation, consumer behavior, and regulatory policies, the study addresses important gaps in the literature and offers practical guidance for firms and policymakers aiming to achieve both sustainability and competitiveness.

2.2. Consumer behavior

Companies and policymakers have many reasons to be interested in understanding the drivers of sustainable consumer behavior. The consumer demand for sustainable options has been on the rise [1]. Consequently, businesses capable of adapting to the rising market demand for sustainability are expected to succeed in the long run [29,30]. For instance, it was found that introducing environmentally sustainable ("green") new products leads to more favorable attitudes toward the brand [31].

Sustainable consumer behavior can be manifested in choosing products with sustainable features [32,33], conserving energy, water, and products during use [34,35]; and utilizing more sustainable modes of product disposal [29,36]. A key determinant of consumers' choice of green products is their environmental awareness and green values. In line with the Theory of Planned Behavior (TPB, Ajzen [37]), it has been shown that pro-environmental sentiments and attitudes often drive the personal norms of consumers, which in turn lead to pro-environmental behaviors such as seeking out or purchasing environmentally friendly products [38,39]. Consequently, individual-level factors including consumers' environmental awareness [2], environmental attitudes and values [40] have been found to predict more favorable responses to environmentally friendly products. So, in the current research, we model two consumer segments based on their environmental awareness levels.

After consumers purchase a product, the environmental impact they create continues during the product usage phase [41]. For instance, life cycle assessment studies indicate that the use phase contributes between 50% and 80% of the total life cycle impacts, as seen in examples like household electrical devices [42]. Consumer behavior at the use phase has been explicitly modeled for products for which the environmental impact generated during the use phase is relatively high such as energy-using appliances [5] and detergents [3,6].

Purchasing a green product can either reinforce or undermine subsequent environmentally responsible behavior in the product use phase. The key determinant of how consumers use the product is their environmental consciousness level [43]. Specifically, for consumers with a high level of environmental consciousness, purchasing a green product bolsters their self-perception as environmentally conscious and reinforces responsible product use behavior. However, for consumers with a low level of environmental consciousness, purchasing a green product satisfies the goal of doing something good for the environment and gives them a license to act in a less environmentally friendly way while they use the product. In the current research, we model the impact of consumer behavior with a parameter that reflects consumers' use-phase efficiency.

In the current research, we resort to consumer behavior research to explore the impact of consumer behavior on both product purchase and usage phases. Specifically, we conduct an experiment to estimate the probable segment size of green consumers, evaluate the impact of a product's environmental friendliness on consumers' WtP value, and explore the extent to which a consumer's level of environmental awareness influences this impact.

2.3. Regulatory incentives

Environmental innovations involve an externality dimension that diminishes the motivation for companies to allocate resources to green products: the advantages of environmental innovation accrue to society as a whole, whereas the associated design and manufacturing costs are predominantly shouldered by individual firms [44,45]. Therefore, markets may fail to incentivize firms to explore environmental innovations. Vernier et al. [46] present an econometric analysis of a survey involving companies that have adopted sustainable product design to demonstrate that regulatory compliance plays a pivotal role in attaining enhanced financial results.

A regulatory agency may introduce incentives or penalties to achieve specific environmental targets. These measures aim to limit the negative environmental impact of products while minimizing regulatory costs. For example, Cohen et al. [47] model a subsidy program of a regulatory decision maker "… *in order to stimulate sales [of EVs] to reach a given adoption target*" while considering the manufacturing industry's pricing and production quantity responses along with the resulting market demand.

Cases of greener products having a positive environmental impact range from solar panels with higher efficiencies to sustainable building materials that reduce the negative environmental impact of the construction process. On the other hand, the positive environmental impact the firm anticipates to achieve with a greener product could fail to materialize due to the behavior consumers may exhibit in the use phase of the product or demand expansion [48]. Jaehn and Meissner [49] examine rebound effects in logistics and propose a method to quantify the actual environmental impact of fuel efficiency improvements, considering how decision-makers adjust their choices within the modified solution space created by these improvements. Koehler and Wildbolz [3] present a life-cycle assessment of home-care and personal-hygiene products and identify global-warming potentials and overall environmental footprints of nine products ranging from bar soaps to liquid detergents. Through a scenario analysis, Koehler and Wildbolz [3] study the impact of consumer behavior too, and argue that overdosing of liquid detergents could substantially increase products' global warming potential and degrade the environmental footprint score. Chapotot et al. [4] focus on the "directions for use" the manufacturers provide for laundry detergents and illustrate the reversal in their environmental benefits when consumers' real use-phase behavior differ from the ideal use-phase behavior specified in the form of "directions for use". The manufacturer may choose to promote the green product assuming that the product consumption would be in line with "directions for use", because the negative environmental impact that real use-phase behavior brings about is an external cost for the firm. When a gap between planned and actual behavior exists, and regulatory agencies may step in with a mechanism to ensure that consumers' real use-phase behavior is taken into consideration in the product design process.

Externality of certain environmental costs forces regulators to institute mechanisms, such as the "Proposal for Ecodesign for Sustainable Products Regulation" of the European Commission [50],"to reduce the negative life cycle environmental impacts of products". For example, in Annex I of the report, "ease of upgrading, re-use, remanufacturing and refurbishment" is listed as one of the parameters that can be "used as a basis for improving the product aspects". As a precursor of EU's regulation, In 2020, German Federal Environment Agency (UBA), citing a violation of Germany's "Battery Act", issued a fine of twelve million Euros against Tesla [51]. Such fines can have an impact on manufacturer's technology selection decisions, for example, in the case of lithium-ion batteries for electric vehicles (EV), less energy-efficient LFP cell chemistry is shown to be safer and to have longer life cycles than NCA and NMC cell chemistries [52]. From the perspective of a consumer, the most important attribute of an EV could be its range, and the manufacturers may respond to this preference by relying more on NCA and NMC cell chemistries. On the other hand, the regulatory agency may be more concerned about recyclability or safety issues, and, through its incentives, it can try to increase the use of LFP cell chemistry.

Lifset et al. [53] argue that incentives based on the inherent characteristics of products can broaden "the scope of Extended Producer Responsibility (EPR)". In other words, they view EPR as an approach that assigns responsibility for a product's environmental performance throughout its entire life cycle, not just an environmental policy approach that assigns producers the responsibility for managing the waste associated with their products and packaging throughout the product's life cycle. Vermeulen et al. [54] discuss three pathways for improving EPR for the circular economy and argue that financial mechanisms should reward front-runners in sustainable product design, creating a stronger incentive for producers to adopt sustainable product attributes such as the share of recycled content. In line with the arguments presented in [53,54], the models we present in Sections 3 and 5 aim to integrate a firm's product line decisions with the incentive schemes set by regulatory agencies, which are linked to the environmental performance of the products.

3. Methods

3.1. Model preliminaries

We consider a market where a consumer's WtP value for the regular (or, interchangeably "brown") product, v, is a random variable which has a uniform distribution over the interval $[0,1]$, i.e., $v \sim U[0,1]$. We allow for discrete heterogeneity in the extent of environmental awareness: a consumer can have "Low" ("High") environmental awareness with probability δ_L ($\delta_H = 1 - \delta_L$) where $0 \leq \delta_L \leq 1$. To simplify the exposition, in the remainder of the paper, we let $\delta_L = \delta$ and $\delta_H = 1 - \delta$ (a summary table of variables and parameters is provided in Appendix A).

The firm has the option of extending its product line with a "green" product. An important decision for the firm is the level of the environmental impact that the green product will have relative to the regular product. Let q_e be the "greenness" level of the green product. We represent the environmental impact of the product when its "greenness" level is q_e with the function $EI(q_e)$. $EI(\cdot)$ maps the "greenness" level of the product to environmental impact which is expressed in terms of an Environmental Performance Indicator (EPI). In other words, $EI(0)$ indicates the environmental impact of the regular product in terms of the selected EPI, and $EI(q_e)$ expresses the environmental impact of a green product whose greenness level is q_e. As discussed in Section 2.3, there may be discrepancies between consumers' actual and ideal behaviors during the use phase, leading to a divergence between anticipated and actual environmental impacts of the green product. Let η_L (η_H) be the “efficiency” of an L (H)–type consumer in the use phase of the green product. With a fully efficient consumer ($\eta_L = 1$ or $\eta_H = 1$), the green product's environmental impact is $EI(q_e) = EI(0) - q_e = e - q_e$, where e denotes the environmental impact of the regular product. With a partially efficient consumer ($\eta_L < 1$ or $\eta_H < 1$), the green product's environmental impact becomes $EI(q_e) = e - \eta_L q_e$ or $EI(q_e) = e - \eta_H q_e$.

Let p_R be the price the firm sets for the regular product. Because $v \sim U[0,1]$, we assume that $0 \le p_R \le 1$. The price of the green product, another decision variable for the firm, will be denoted by p_G, where $p_G = p_R + p_\Delta$, and $p_\Delta \ge 0$. The firm's objective is to select the profit-maximizing prices p_R and p_G (or p_Δ), and the greenness level q_e of the green product. To pave the way for an expression of the firm's the profit function, the consumer choice model and demand functions will be described in the next two subsections.

3.1.1. Consumer choice model

We assume that the customers of both segments, namely segments with high and low environmental awareness, seek to maximize their utility. Let $u_{H,R}(v)$ ($u_{L,R}(v)$) and $u_{H,G}(v)$ ($u_{L,G}(v)$) represent the utility a consumer with high (low) environmental awareness and a WtP value of v will obtain when purchasing the regular and the green products, respectively.

With the purchase of the regular product, a consumer with a WtP value of v, regardless of whether she has high or low environmental awareness, will derive a utility of $v - p_R$, i.e., $u_{H,R}(v) = u_{L,R}(v) = v - p_R$. In other words, we assume that the regular product does not offer any features that could alter the utility of consumers that exhibit high or low environmental awareness.

The green product is designed to deliver a higher level of environmental performance, and its impact on the utility of a consumer will be a function of its level of greenness and the extent of the consumers' environmental awareness. We note that the greenness level is stipulated by the manufacturer under the assumption that consumer use-phase behavior would be aligned with its recommendations.

We assume a positive relationship between the degree of a consumer's environmental awareness and the additional utility derived from a green product. Let $\alpha \ge 0$ represent the degree of a specific consumer's environmental awareness. For this individual, the function $UI(\alpha, q_e) \ge 0$, where $q_e \ge 0$ and $\alpha \ge 0$, indicates the utility impact of a product with a specified level of greenness, q_e. The functional form of $UI(\cdot,\cdot)$, in line with the analysis of Bei and Simpson [55], will be assumed to be linear in q_e: $UI(\alpha, q_e) = \alpha q_e$.

Consequently, a consumer with a WtP value of v, and an environmental awareness level α, will experience a net utility of $v + UI(\alpha, q_e) - p_G$ upon purchasing the green product. In essence, purchasing the green product augments the consumer's utility additively. This assumption is consistent with the model proposed by Gao and Souza [56], which incorporates a constant, positive term in the utility functions of environmentally sensitive consumers. According to Gao and Souza [56], the environmental performance of a product does not influence its perceived intrinsic quality or functionality from the consumer's perspective. Consequently, it does not alter consumers' fundamental WtP. Their model integrates enhancements in environmental performance into an additive utility function. A consumer choice model for the case where the green product serves as an alternative to the regular product in terms of its perceived intrinsic quality is presented in [12]. A non-negative scale parameter captures the relative intrinsic quality of the green product compared to the regular product and if the parameter's value is smaller (greater) than one the regular product exhibits superior (inferior) intrinsic quality to the green product. Liu [12] also assumes that for consumers with higher environmental awareness the additional utility of the green product is constant. For the fixed intrinsic quality case [56], the consumer choice model we employ allows the manufacturer use the greenness level (or “quality”) of the product, along with its price, as a critical decision variable to shift the demand for the green product.

We represent the variability in the level of environmental awareness using a two-segment market model, where α_H and α_L denote the environmental awareness parameters for consumers with higher and lower levels of awareness, respectively. When purchasing a green product, a consumer with a WtP value of v and high (low) awareness, will derive a utility of $u_{H,G}(v) = v + \alpha_H q_e - p_G$ ($u_{L,G}(v) = v + \alpha_L q_e - p_G$). Since the function $UI(\alpha, q_e)$ merely scales the product's green attribute by α_H or α_L, we simplify the exposition by setting $\alpha_H = 1$ and $\alpha_L = \alpha$, where $0 \le \alpha < 1$, without any loss of generality for the rest of the paper.

3.1.2. Product demands

With the consumer choice model defined in Section 3.1.1, we proceed to analyze the product demands a firm encounters upon selecting specific values for p_R, p_Δ, and q_e. In this study, $D_H^R(p_R, p_\Delta, q_e)$ and $D_H^G(p_R, p_\Delta, q_e)$ ($D_L^R(p_R, p_\Delta, q_e)$ and $D_L^G(p_R, p_\Delta, q_e)$) represent the demand from the consumer segment characterized by high (low) environmental awareness for regular and green products, respectively.

A consumer in the high awareness segment and with a WtP value of v purchases the regular product only when (1) $u_{H,R}(v) = v - p_R \ge 0$, and (2) $u_{H,R}(v) > u_{H,G}(v)$. Because $v \sim U[0,1]$, first condition requires that $v \in [p_R, 1]$. Noting that α_H is assumed to be equal to one, the second condition can be stated as

$$v - p_R > v + q_e - (p_R + p_\Delta) \Rightarrow p_\Delta > q_e \Rightarrow \frac{p_\Delta}{q_e} > 1.$$

Similarly, a consumer in the low awareness segment purchases the regular product when (1) $u_{L,R}(v) = v - p_R \ge 0$ and (2) $u_{L,R}(v) > u_{L,G}(v)$. These conditions can be restated as $v \in [p_R, 1]$ and

$$v - p_R > v + \alpha q_e - (p_R + p_\Delta) \Rightarrow p_\Delta > \alpha q_e \Rightarrow \frac{p_\Delta}{q_e} > \alpha.$$

On the other hand, a consumer in the high awareness segment and with a WtP value of v purchases the green product only when (1) $u_{H,G}(v) = v + q_e - (p_R + p_\Delta) \ge 0$, and (2) $u_{H,G}(v) > u_{H,R}(v)$. These two conditions can be stated as $v \in [p_R + p_\Delta - q_e, 1]$ and $\frac{p_\Delta}{q_e} \le 1$. In a similar manner, a consumer in the low awareness segment and with a WtP value of v, purchases the green product only when $v \in [p_R + p_\Delta - \alpha q_e, 1]$ and $\frac{p_\Delta}{q_e} \le \alpha$.

We can now describe three purchase scenarios:

Case 0 When $\frac{p_\Delta}{q_e} > 1$, we also have $\frac{p_\Delta}{q_e} > \alpha$, and both segments purchase the regular product, and we observe the following product demands: $D_H^R(p_R, p_\Delta, q_e) = (1-\delta)(1-p_R)$, $D_H^G(p_R, p_\Delta, q_e) = 0$, $D_L^R(p_R, p_\Delta, q_e) = \delta(1-p_R)$, and $D_L^G(p_R, p_\Delta, q_e) = 0$.

Case 1 When $\alpha < \frac{p_\Delta}{q_e} \le 1$, the high awareness segment purchases the green product only. For a consumer in the high awareness segment with a WtP of v, the utility with the green product will be equal to $u_{H,G}(v) = v + q_e - (p_R + p_\Delta)$, generating a green product demand of $D_H^G(p_R, p_\Delta, q_e) = (1-\delta)(1 - p_R - p_\Delta + q_e)$. As in Case 1, the low awareness segment purchases the regular product only and generates a regular product demand of $D_L^R(p_R, p_\Delta, q_e) = \delta(1-p_R)$ and green product demand of $D_L^G(p_R, p_\Delta, q_e) = 0$.

Case 2 When $\frac{p_\Delta}{q_e} \le \alpha \le 1$, high and low awareness segments purchase the green product only and generate a green product demand of $D_H^G(p_R, p_\Delta, q_e) = (1-\delta)(1 - p_R - p_\Delta + q_e)$ and $D_L^G(p_R, p_\Delta, q_e) = \delta(1 - p_R - p_\Delta + \alpha q_e)$, respectively.

The cases discussed above and illustrated over the $(\frac{p_\Delta}{q_e}, \alpha)$ space in Fig. 1 demonstrate the influence of the $\frac{p_\Delta}{q_e}$ ratio on the shifts in demand: when the difference between green and regular products' prices is smaller than the utility impact of a greenness level of q_e on the low awareness segment (i.e., $UI(\alpha, q_e) = \alpha q_e$), both segments purchase the

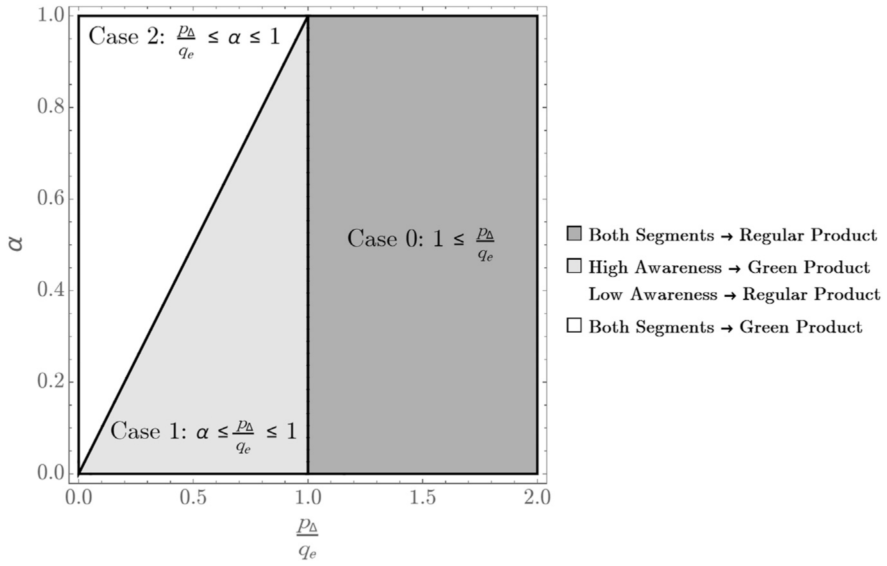


Fig. 1. Demand regions and transitions over the $(\frac{p_\Delta}{q_e}, \alpha)$ space.

green product. On the other hand, if the price difference is higher than the utility impact of a greenness level of q_e on the high awareness segment (i.e., $UI(1, q_e) = q_e$), both segments end up purchasing the regular product. In our setting, each consumer makes a discrete choice between purchasing the regular product, purchasing the green product, or not purchasing at all. The demand-region boundaries identify the conditions under which a consumer is indifferent between these options and therefore delineate which choice is optimal for each segment. These boundaries represent analytical indifference conditions rather than literal discontinuities in behavior.

The preceding discussion has demonstrated how product demands are influenced by the manufacturer's decisions, i.e., p_R, q_e, and p_Δ, alongside two critical, exogenous parameters: α and δ. Importantly, all policy and managerial insights in the paper are derived within demand regions, where demand varies continuously with prices and greenness, and do not depend on knife-edge boundary conditions. Section 4 will detail an experiment conducted to estimate the values of these parameters for a specific product category, setting the stage for the presentation of the manufacturer's problem in Section 5.

4. Experiment

This experiment has three main goals: to estimate the probable segment size of green consumers (δ), to evaluate the impact of a product's environmental friendliness (q_e) on consumers' WtP value (v), and to test whether green customers respond differently to environmentally friendly products (α). The study focuses on "laundry detergent" as the product category under investigation. Participants are provided with descriptions of regular, concentrated, or extra concentrated liquid detergents. Subsequently, they express their WtP for the specified products. Finally, the study assesses participants' environmental awareness and gathers demographic data. Preregistration information for this study is presented in [57]. Full text of product greenness manipulations and details of analysis results are presented in Appendix B.

4.1. Method

This study employed a between-participants design with a single factor (product greenness: regular vs. concentrated vs. extra concentrated). We recruited 697 participants residing in the U.S. through the Amazon Mechanical Turk platform in exchange for a nominal payment. Eight participants were excluded for failing a simple attention check. This resulted in a final sample of 689 participants ($M_{Age} = 43.05$, 46.2% Female).

Participants were informed that they would receive information about a new liquid detergent and answer questions related to that. Briefly, participants in the regular detergent condition were presented with the following information:

> *. . . one of the brands that you frequently buy renewed its bottle to make it more user-friendly. It is a regular liquid detergent, not concentrated. . . It comes in a new 100 oz bottle, that washes approximately 64 loads.*

Participants in the concentrated [extra concentrated] detergent condition were provided with the following information:

> *. . . one of the brands that you frequently buy launched a new environmentally friendly [extra] concentrated liquid detergent. This [extra] concentrated liquid detergent has reduced impact on the environment thanks to 25% [50%] less water used in production, 30% [60%] less plastic and paper used in packaging, and 16% [32%] less carbon footprint overall. ...It comes in a new 64 [50] oz bottle, that washes approximately 64 loads.*
>
> *The positive environmental impact of using a concentrated liquid detergent instead of a regular one is tremendous. If every household in the United States switches to the concentrated detergent, just within a year, total reduction in carbon dioxide (CO_2) emission will be roughly equal to the amount of CO_2 emission caused by 200,000 [400,000] cars in that time.*

Participants indicated the maximum amount they would be willing to pay for the detergent using a slider scale ranging from \$5 to \$30. To assess the impact of our manipulation on perceived product greenness, participants evaluated the environmental friendliness of the detergent on a scale from 1 ("not at all") to 9 ("to a great extent"). We measured participants' environmental awareness using a 12-item scale (e.g., "I try to separate trash for recycling on a regular basis", "I prefer to use environmentally friendly products"; 1 = "strongly disagree"; 7 = "strongly agree"), adapted from [58]. Demographic data, including participants' age and gender identity, were also collected.

4.2. Results

We begin our analysis by determining if participants can be segmented based on their scores from the environmental awareness scale. To classify participants according to their level of environmental awareness, we conduct a K-means cluster analysis using their mean environmental awareness scores. A two-cluster solution is specified, resulting in one group characterized by low awareness (30.9%) and another by high awareness (69.1%). The difference in environmental awareness between the two clusters is significant ($M_{LowAwareness} = 3.08, SD = 0.92$; $M_{HighAwareness} = 5.39, SD = 0.79$; $F(1687) = 1256.83, p < .001, \eta_p^2 = 0.65$), indicating successful differentiation, hence the existence of two segments. Then, we examine the influence of product greenness on consumer willingness to pay (WtP). A one-way ANOVA reveals a significant effect of product greenness on WtP ($M_{Regular} = 11.65, SD = 3.04$; $M_{Concentrated} = 13.42, SD = 3.87$; $M_{ExtraConcentrated} = 13.31, SD = 4.68$; $F(2686) = 14.73, p < .01, \eta_p^2 = 0.04$). Specifically, post-hoc tests indicate that consumers are prepared to pay significantly more for concentrated and extra concentrated detergents than for the regular detergent ($ps < .01$). However, the WtP difference between concentrated and extra concentrated detergents is not significant ($p > .7$). The absence of a significant difference between the concentrated and the extra concentrated detergents may be attributed to the negligible perceived difference ($p > .6$) between the greenness levels of them in the between-participants setting of the experiment.

Last, we use environmental awareness cluster membership as a categorical predictor to examine whether it influences the difference in WtP values for regular and concentrated detergents. A 2 (environmental awareness) × 3 (product greenness) ANOVA using WtP as the dependent variable reveals significant main effects of both environmental awareness and product greenness ($F(1683) = 57.11, p < .001, \eta_p^2 = 0.08$; $F(2683) = 7.08, p < .001, \eta_p^2 = 0.02$, respectively). Importantly, we find a significant interaction between environmental awareness and product greenness ($F(2683) = 7.89, p < .001, \eta_p^2 = 0.02$; Fig. 2). Pairwise comparisons show that for both concentrated and extra concentrated detergents, participants with high (vs. low) environmental awareness are willing to pay more ($M_{LowAwareness} = 11.55, SD = 4.05, M_{HighAwareness} = 14.16, SD = 3.55$; $F(1683) = 22.65, p < .01, \eta_p^2 = 0.03$; $M_{LowAwareness} = 10.78, SD = 3.61, M_{HighAwareness} = 14.45, SD = 4.67$; $F(1683) = 47.12, p < .01, \eta_p^2 = 0.065$, respectively). Whereas, for the regular detergent, there is no significant difference in WtP between high and low environmental awareness groups ($M_{LowAwareness} = 11.16, SD = 2.3, M_{HighAwareness} = 11.9, SD = 3.34$; $F(1683) = 1.97, p > .1, \eta_p^2 < 0.01$).

This experimental study within a specific product category, liquid detergents, supports the hypothesis that the "greenness" of a product could statistically significantly increase consumers' WtP values. Additionally, the findings reveal the existence of two distinct consumer segments with different environmental awareness levels. These two consumer segments exhibit varied responses to product greenness, highlighting the importance of targeting strategies in the context of product line design.

5. Manufacturer's problem under regulatory incentives

Having substantiated the core assumptions of our model, we turn to the manufacturer's problem. Utilizing the demand functions outlined in Section 3.1.2, we formulate the manufacturer's objective function in terms of its decision variables, namely p_R, p_G (or p_Δ), and q_e, alongside the pertinent cost parameters characterizing the operating environment.

Let c_R represent the unit production cost of the standard product. Consequently, the contribution margin of the standard product is $p_R - c_R$. For the purposes of this analysis, we will assume, without loss of generality, that c_R is zero. Therefore, the contribution margin of the standard product simplifies to its price, i.e., p_R.

The manufacturing cost of a green product is assumed to be a convex (quadratic) function of its greenness level, as selected by the firm. This structure is widely adopted in the sustainable product-design literature (e.g., [7,9,56]) because it captures the increasing marginal investment required to enhance environmental quality and ensures interior optimal solutions. Accordingly, following Chen [7], we represent the unit production cost as $c_q q_e^2$, where $c_q > 0$ denotes the cost coefficient.

As introduced in Section 3.1, $EI(q_e)$ states the environmental impact of a product whose "greenness" level is q_e. $EI(\cdot)$ is expressed in terms of an EPI such as the extent of product's GHG emissions or marine aquatic toxicity when it is used in line with the manufacturer's instructions. Under the "ideal" use-phase behavior of the customers, green product delivers a better performance with respect to the focal EPI of the regulatory agency, i.e., $EI(0) > EI(q_e)$, and, for every green product it sells, the firm would receive an incentive of $m_e(EI(0) - EI(q_e))$ where m_e is the financial incentive the regulatory agency offers per unit reduction in the focal EPI. This incentive structure modifies the marginal return to greenness in the manufacturer's optimization problem. A practical illustration of a performance-linked regulatory incentive is the California Zero-Emission Vehicle (ZEV) credit system [59], under which manufacturers earn tradable credits per vehicle sold based on emissions-related performance. Because these credits have monetary value and vary with environmental performance, they alter the marginal return to producing cleaner vehicles. A similar logic applies in EPR schemes, where producers pay per-unit fees that are explicitly differentiated according to measurable product attributes such as recyclability or durability ([60], Tables 4 and 8). In both cases, the regulatory instrument operates as a performance-dependent, per-unit monetary adjustment that modifies the firm's effective marginal cost or benefit of product design. This economic structure corresponds directly to the incentive parameter m_e in our model, which captures such marginal, performance-linked regulatory adjustments in reduced form.

In this section, to simplify the exposition, we assume that $\eta_L = 1$ and $\eta_H = 1$, i.e., consumers are fully efficient in the use phase, and we let $EI(0) = e$ and $EI(q_e) = e - q_e$.

The contribution margin of the green product can then be stated as $p_G - c_q q_e^2 + m_e(EI(0) - EI(q_e))$ or $p_R + p_\Delta - c_q q_e^2 + m_e(EI(0) - EI(q_e))$. When $EI(0) = e$ and $EI(q_e) = e - q_e$, the contribution margin reduces to $p_R + p_\Delta - c_q q_e^2 + m_e q_e$.

Based on the contribution margin established above, the firm's optimization problem can now be stated as

$$\begin{aligned}\max_{p_R,p_\Delta,q_e} \Pi_M(p_R,p_\Delta,q_e) = \Big[\, & p_R\left[D_H^R(p_R,p_\Delta,q_e) + D_L^R(p_R,p_\Delta,q_e)\right] + \\ & \left(p_R + p_\Delta - c_q q_e^2 + m_e q_e\right) \times \\ & \left[D_H^G(p_R,p_\Delta,q_e) + D_L^G(p_R,p_\Delta,q_e)\right]\Big],\end{aligned} \tag{1}$$

where $\Pi_M(p_R,p_\Delta,q_e)$ denotes the profit of the firm.

Let $\Pi_M(p_R^*, p_\Delta^*(m_e), q_e^*(m_e)) = \max_{p_R,p_\Delta,q_e} \Pi_M(p_R,p_\Delta,q_e)$. To derive closed-form expressions for $p_R^*, p_\Delta^*(m_e)$ and $q^*(m_e)$, a multitude of scenarios need to be taken into consideration:

Case 1 An H-type consumer purchases the green product with a probability strictly smaller than 1 (i.e., some H-type consumers do not purchase any product), and L-type consumers purchase the regular product only,

Case 2 An H-type consumer purchases the green product with a probability strictly smaller than 1 (i.e., some H-type consumers do not purchase any product), and L-type consumers purchase the green product only,

Case 3 H-type consumers purchase the green product with probability 1 (i.e., all H-type consumers do purchase the green product), and L-type consumers purchase the regular product only,

Case 4 H-type consumers purchase the green product with probability 1 (i.e., all H-type consumers do purchase the green product), and L-type consumers purchase the green product only.

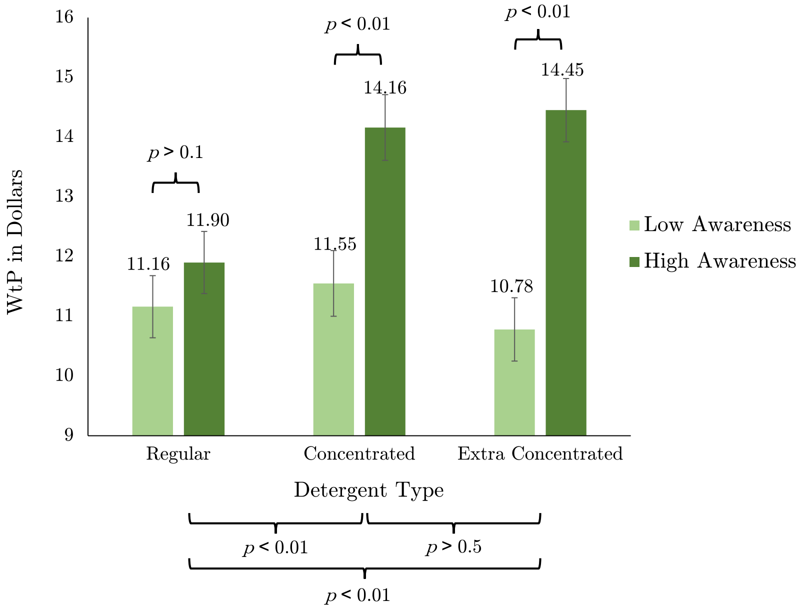


Fig. 2. Effect of consumer environmental awareness and product greenness on WtP.

We note that Cases 1 and 2 above are from Section 3.1.2, and Cases 3 and 4 are their extensions with the additional demand realizations of H-type consumers in the form of $1 - p_R - p_\Delta + q_e = 1$. We note that, because $0 \leq \alpha < 1$, the green product demand of L-type consumers is always smaller than that of the H-type consumers, i.e., $1 - p_R - p_\Delta + \alpha q_e < 1 - p_R - p_\Delta + q_e$. Therefore, it suffices to consider the case of $1 - p_R - p_\Delta + q_e = 1$, i.e., the case where all H-type consumers purchase the green product.

The scenarios can be further generalized by considering the market segments that the manufacturer targets during the design of the green product. For example, in the design process of the green product, the manufacturer might prioritize Case 2, determining the optimal values of the decision variables — namely p_R^*, p_Δ^*, and q_e^* — to maximize profits from selling the green product to both consumer types. Conversely, under certain cost parameters that characterize the operating environment, the optimal values of the decision variables for Case 1 — where the green product is designed with anticipation of demand from only type H consumers — might also attract demand from both customer types. We will present an illustrative example following the discussion of the optimal values of the decision variables.

In the first column of Table 1, we present all feasible scenarios using a notation with three fields. The initial field specifies the design focus: either targeting both consumer types ($L + H$) or exclusively targeting consumers with high environmental sensitivity (H). The second field captures the demand of L-type consumers for the green product, with “0” indicating no demand and “$\gtrless$” signifying that the probability of an L-type consumer purchasing the green product lies within the interval (0,1). The third field addresses the demand of H-type consumers for the green product, where “1” means all H-type consumers purchase the green product and “$\gtrless$” indicates that the purchase probability for an H-type consumer is in the interval (0,1). In the second and third columns of Table 1, we report the optimal values of q_e^* and p_Δ^* for each scenario. We note that, because we have assumed that $c_R = 0$, p_R^* can be readily shown to be equal to $\frac{1}{2}$. In the final column of Table 1, we provide the ranges of problem parameters across which each scenario is observable. The derivations for all results are detailed in the Appendix C. As will be discussed in Section 6, our objective is to solve the regulatory agency’s incentive design problem, in which the manufacturer’s optimal decisions in response to a given incentive level m_e are embedded within the regulatory agency’s optimization framework. A detailed discussion of the computational complexity associated with the regulatory agency’s optimization problem is provided in Section 6.

Fig. 3 illustrates possible scenarios in the (m_e, c_q) space for a problem instance with $\alpha = \delta = 0.5$, $e = 5$, and $\eta_L = \eta_H = 1$. In the left (right) side of the figure, we illustrate the feasibility regions for scenarios where the green product is designed to target both high- and low-awareness segments (only the high-awareness segment). A scenario shown in Fig. 3 may dominate another when both are feasible within the same region. For example, in regions where both scenarios $L + H|0| \gtrless$ and $H|0| \gtrless$ are feasible, it can be readily shown that scenario $H|0| \gtrless$ would be the better one for the manufacturer. Similarly, when scenarios $L + H|\gtrless| \gtrless$ and $H|\gtrless| \gtrless$ are both feasible in a region, scenario $L + H|\gtrless| \gtrless$ would yield a higher profit for the manufacturer. While these dominance relationships help eliminate some scenarios in specific regions, the overall complexity of the problem remains high and can be better understood by superimposing the left side of the figure onto the right.

In the preceding analysis, we have considered m_e as an exogenous parameter for the manufacturer, alongside other parameters such as α, δ, e, η_L and η_H. The parameter m_e is a crucial decision variable for the regulatory agency. In the subsequent section, we present a model that the agency can employ to determine the value of m_e.

6. Regulatory agency’s incentive design problem

The regulatory agency may offer incentives to achieve specific environmental improvement targets (or penalties to keep adverse environmental impacts below established thresholds), while minimizing the costs associated with the incentives. In this study, we assume that the regulatory agency operates within a complete-information framework, allowing it to fully anticipate the impact of a specific value of m_e on both the price and greenness level of the green product as determined by the manufacturer. Before we represent the net effect of these regulatory adjustments, we note that m_e captures regulatory instruments that operate through marginal, performance-dependent monetary adjustments linked to environmental performance. It does not represent lump sum grants that are independent of product design, nor purely consumer-side rebates that do not affect the firm’s marginal greenness incentives. The analysis focuses on policy instruments that directly influence manufacturer decisions by altering the marginal cost or benefit of improving environmental performance.

As described earlier, $EI(q_e)$ is the environmental impact of the product when its “greenness” level is q_e, expressed in terms of an EPI. To simplify the exposition, we focus on the Scenario 1 (See Table 1)

Table 1
Design and demand scenarios.

Scenario		q_e^*	p_Δ^*	Parameter ranges
1	$L+H\ \lvert\gtrless\rvert\gtrless$	$\frac{1+m_e-\delta(1-\alpha)}{2c_q}$	$\frac{3-m_e-3\delta(1-\alpha)}{4}\times q_e^*$	$3-4\alpha-3\delta(1-\alpha)\le m_e\le 3(1-\delta(1-\alpha))\wedge c_q\ge\frac{(1+m_e-\delta(1-\alpha))(1+m_e+3\delta(1-\alpha))}{4}$
2	$L+H\ \lvert\gtrless\rvert 1$	$\tilde{p}^1+p_R^*$	$\tilde{p}$	$\frac{4(1+m_e)(1-\alpha)(1-\delta)}{4-3\delta}\le c_q\le\frac{4(1+m_e)(1-\delta(1-\alpha))}{4-3\delta(1-\alpha)}$
3	$H\ \lvert 0\rvert\gtrless$	$\frac{1+m_e}{2c_q}$	$\frac{3-m_e}{4}\times q_e^*$	$-1\le m_e<3-4\alpha\wedge c_q\ge\frac{(1+m_e)^2}{4}$
4	$H\ \lvert 0\rvert 1$	$\frac{1+m_e-c_q}{2c_q}+p_R^*$	$\frac{1+m_e-c_q}{2c_q}$	$-1<m_e\wedge c_q<(1-\alpha)(1+m_e)$
5	$H\ \lvert\gtrless\rvert\gtrless$	$\frac{1+m_e}{2c_q}$	$\frac{3-m_e}{4}\times q_e^*$	$c_q\ge\frac{(1+m_e)^2}{4}\wedge 3-4\alpha\le m_e\le 3$
6	$H\ \lvert\gtrless\rvert 1$	$\frac{1+m_e-c_q}{2c_q}+p_R^*$	$\frac{1+m_e-c_q}{2c_q}$	$1+m_e\ge c_q\ge(1+m_e)(1-\alpha)$
7	$L+H\ \lvert 0\rvert\gtrless$	$\frac{1+m_e-\delta(1-\alpha)}{2c_q}$	$\frac{3-m_e-3\delta(1-\alpha)}{4}\times q_e^*$	$(m_e=\delta(1-\alpha)-1\wedge c_q>0)\vee(\delta(1-\alpha)-1<m_e<3(1-\delta(1-\alpha))-4\alpha\wedge c_q\ge\frac{(1+m_e-\delta(1-\alpha))(1+m_e+3\delta(1-\alpha))}{4})$
8	$L+H\ \lvert 0\rvert 1$	$\tilde{p}+p_R^*$	$\tilde{p}$	$0<c_q<\frac{4(1+m_e)(1-\alpha)(1-\delta)}{4-3\delta}$

$1:\tilde{p}=\frac{-2c_q-\delta(1-\alpha)\left(2(1+m_e)-3c_q\right)+2\sqrt{c_q^2-\delta(1+m_e)(1-\alpha)\left(c_q-\delta(1+m_e)(1-\alpha)\right)}}{6c_q\delta(\alpha-1)}$

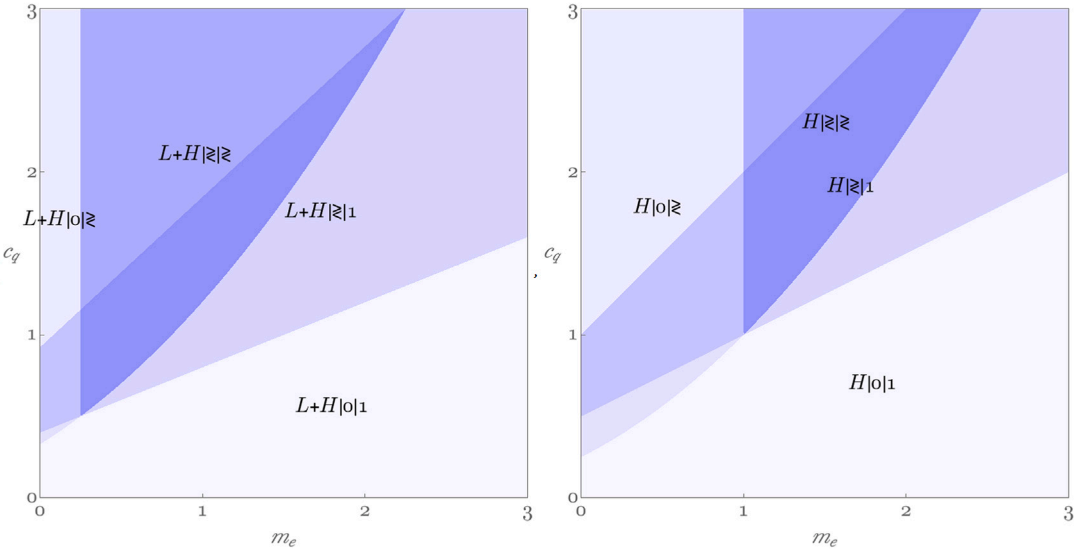


Fig. 3. Design and demand scenarios and feasibility ranges.

where $\eta_H=\eta_L=1$ and both segments purchase the green product when $m_e=0$, i.e., we assume that $\alpha\le\frac{p_\Delta}{q_e(0)}<1$, and the impact of the green product is positive with $EI(q_e)=e-q_e$. All other cases are reported in Table 1.

Let $\widetilde{D}_H^G(m_e)=D_H^G(p_R^*(m_e),p_\Delta^*(m_e),q_e^*(m_e))$ and $\widetilde{D}_L^G(m_e)=D_L^G(p_R^*(m_e),p_\Delta^*(m_e),q_e^*(m_e))$ be the demands of the high and low awareness segments, respectively, for the green product.

The regulatory agency's objective is to minimize the total cost of incentives while achieving $B\times 100$ percent ($0\le B\le 1$) improvement in environmental performance with respect to the case where no such incentive is offered:

$$EMP_1\ :\ z_1^*(m_e^{1^*})=\min_{m_e\ge 0} m_e^1 q_e^*(m_e^1)\left[\widetilde{D}_H^G(m_e^1)+\widetilde{D}_L^G(m_e^1)\right]$$

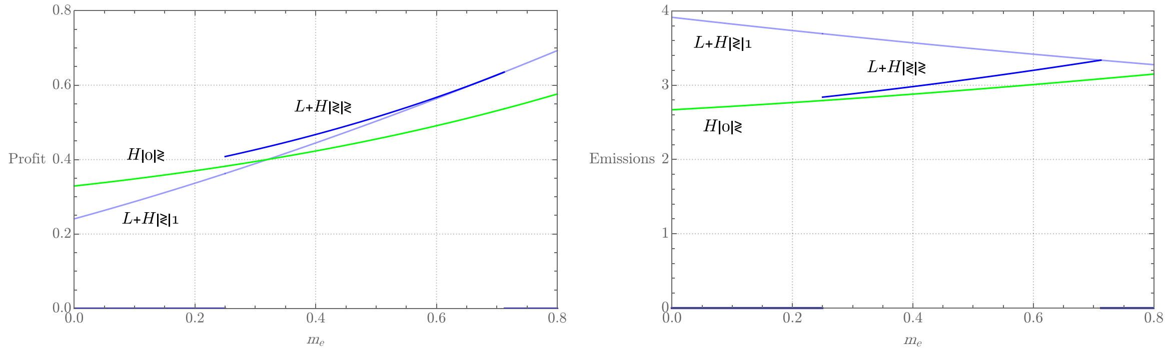
$$\text{s.t.}(e-q_e^*(m_e^1))\left[\widetilde{D}_H^G(m_e^1)+\widetilde{D}_L^G(m_e^1)\right]\le(e-q_e^*(0))\left[\widetilde{D}_H^G(0)+\widetilde{D}_L^G(0)\right](1-B).\tag{2}$$

EMP_1 represents the optimization problem specific to Scenario 1; analogous problems for other scenarios listed in Table 1 can be formulated by aligning the objective function and Constraint (2) with each scenario's demand realizations for the regular and green products, and by accordingly changing the indices of EMP_1, $z_1^*(\cdot)$, $m_e^{1^*}$, and m_e^1. Before discussing the solution to EMP_1 and the regulatory agency's task of determining the optimal value of across all scenarios, we present a numerical example to illustrate the behavior of the *LHS* of Constraint (2).

We consider a problem instance with $c_q=0.9$, $\alpha=\delta=0.5$, $e=5$. Fig. 4(a) reports how the profit function of the manufacturer changes as the incentive, i.e., m_e, increases. When m_e is small, only Scenarios 2 and 3 (i.e., $L+H|\gtrless|1$ and $H|0|\gtrless$) are feasible with the above problem parameters, and the manufacturer opts for Scenario 3 to maximize its profit. As m_e increases, Scenario 1 (i.e., $L+H|\gtrless|\gtrless$) becomes part of the feasible scenario set and yields the highest profit. After Scenario 1 becomes infeasible with larger values of m_e, Scenario 2 starts to yield higher profit than Scenario 1.

Fig. 4(a) illustrates the impact of the incentive m_e on the manufacturer's profit function. When m_e is low, only Scenarios 2 and 3 are viable, with Scenario 3 providing the higher profit. As m_e increases, Scenario 1 becomes feasible and offers the highest profit. However, when m_e reaches higher values, Scenario 1 becomes infeasible, and Scenario 2 yields a higher profit than Scenario 3. We next examine the emissions resulting from the manufacturer's profit-maximizing decisions. Fig. 4(b) clearly illustrates the adverse effects of incentives when they are not accompanied by a specific emissions reduction target. When m_e is low, as previously discussed, the manufacturer's optimal decision is to follow Scenario 3. This scenario leads to an increase in emissions due to the resulting demand expansion, thus negating the intended effect of providing incentives. In other words, for Scenario 3, i.e., in problem EMP_3, the *LHS* of Constraint (2) is non-decreasing in m_e.

This numerical example also illustrates an effective approach for designing an emissions-reducing incentive mechanism. For a given emissions reduction target, regulatory agency must encourage the manufacturer to adopt scenarios for which the *LHS* of Constraint (2) is non-increasing in m_e. Therefore, the incentive — contingent upon achieving



(a) Manufacturer's profit function.

(b) Total emissions.

Fig. 4. The problem of establishing effective incentives.

Table 2

Ranges of parameters over which the *LHS* of Constraint (2) is decreasing in m_e.

Scenario	Ranges of parameters
1	$\left(\left(0 < e \leq \frac{1}{1+m_e-\delta(1-\alpha)} \wedge c_2 > 0\right) \vee \left(e > \frac{1}{1+m_e-\delta(1-\alpha)} \wedge 0 < c_2 < \frac{3(1+m_e-\delta(1-\alpha))^2}{-4+4e(1+m_e-\delta(1-\alpha))}\right)\right)$
2	Always decreasing in Scenario 2.
3	$\left(0 < c_2 < \frac{3(1+m_e)^2}{4(-1+e(1+m_e))} \wedge e > \frac{1}{1+m_e}\right) \vee \left(0 < e \leq \frac{1}{1+m_e} \wedge c_q > 0\right)$
4	Always decreasing in Scenario 4.
5	$0 < e < \frac{4c_q+(1+m_e)(3+3m_e-8\delta(1-\alpha))}{4c_q(1+m_e-2\delta(1-\alpha))} \wedge m_e \leq 3 \wedge \left((m_e \geq 3-4\alpha \wedge 4\alpha \leq 3) \vee (4\alpha > 3 \wedge m_e \geq 0)\right)$
6	$c_q > \frac{\delta(\alpha-1)(1+m_e)}{-1-e\delta(1-\alpha)}$
7	$\left(\left(0 < e \leq \frac{1}{1+m_e+\delta(1-\alpha)} \wedge c_2 > 0\right) \vee \left(e > \frac{1}{1+m_e+\delta(1-\alpha)} \wedge 0 < c_2 < \frac{(3+3m_e+5\delta(1-\alpha))(1+m_e-\delta(1-\alpha))}{-4+4e(1+m_e+\delta(1-\alpha))}\right)\right)$
8	Always decreasing in Scenario 8.

the specified emissions reduction — must be substantial enough to make the selected scenario more profitable for the manufacturer than the scenario it would choose with $m_e = 0$.

Before we proceed with a formal presentation of the regulatory agency's incentive design problem, we present a result on the objective functions of problems EMP_1 through EMP_8:

Proposition 6.1. *The objective function of problem $EMP_i, i = 1, \ldots, 8$, in non-decreasing in m_e.*

A proof of Proposition 6.1 is presented in the Appendix D. After examining the behavior of the objective function in problems EMP_1 through EMP_8 as m_e varies, we now focus on the *LHS* of the Constraint (2). In Table 2, assuming that $\eta_L = \eta_H = 1$, we list the values of problem parameters c_q, α, δ, and e for which the *LHS* of Constraint (2) is decreasing in m_e. A derivation of these ranges is presented in the Appendix E.

In Algorithm 1, we outline a procedure that the regulatory agency can use to determine the incentive value m_e necessary to enhance environmental performance by a factor of $B \times 100$ percent ($0 \leq B \leq 1$), compared to scenario where no incentive is provided. We note that in Scenarios 2, 4, and 8, the optimal solution can be directly generated with a simple univariate bisection approach with a computational complexity of $O(log_2(\frac{m_e^{UB}}{\epsilon}))$ where m_e^{UB} is an upper bound on m_e^* and ϵ is the desired error tolerance. In other scenarios, the optimal solutions can be generated in a similar fashion over the ranges of m_e over which the *LHS* of Constraint (2) is decreasing in m_e.

7. Results and discussion

The stylized model in Section 3 features a multitude of parameters that represent a wide range of real-life scenarios. In this section, we report the results of computational analyses to identify the real-life scenarios that best align with the objectives of regulatory agencies. We first focus on the environmental awareness level of the customers that are in the low awareness segment. We then study the impact of segment sizes and the consumers' use-phase efficiencies. We conclude this section with a discussion on the impact of the manufacturing costs.

7.1. The impact of environmental awareness

In Fig. 5, we study the impact of α, a critical parameter of our setting that reflects the environmental awareness level of the customers that are in the low awareness segment, on various performance indicators. In the left column of Fig. 5 we consider a problem setting with $\alpha = 0.25, \delta = 0.5, e = 2.5, c_q = 1.25$ and $\eta_L = \eta_H = 1$. In the right column we simply set $\alpha = 0.75$ without changing the remaining parameters. In the first row of Fig. 5, we report the changes in the optimal product design strategy of the retailer, the greenness level of the product (i.e., q_e), and the price difference between the regular and green products (i.e., p_Δ) as the government extends incentives to achieve emission reductions. In all graphs, the horizontal axis illustrates the targeted reduction in emissions as a percentage of the emissions observed when no incentive is extended to the manufacturer, i.e., covers the $[0, 0.75]$ range for parameter B of problem $EMP_i, i = 1, \ldots, 8$.

In Fig. 5(a), when the regulatory agency does not impose a reduction target (i.e., the case of "0%" emission reduction target or $m_e = 0$), the firm designs a green product with a greenness level of $q_e^*(0) = 0.4$, and sets a price of $p_R^* + p_\Delta^*(0) = 0.5 + 0.3 = 0.8$ for the green product. The green product is designed in consideration of customers in the high awareness segment, and, because the additional utility of $\alpha \times 0.4 = 0.25 \times 0.4 = 0.1$ derived from the green product is smaller than the additional price of 0.3, customers with the low awareness level do not the purchase the green product; hence, we observe the $H|0|\gtrless$ scenario. The demand source for the green product is the high environmental awareness segment, and a customer in the segment with a valuation above 0.4 would purchase the green product yielding a total green demand of $(1-\delta)\times(1-0.4) = (1-0.5)\times(1-0.4) = 0.3$. On the other hand,

Algorithm 1: The value of m_e that minimizes the regulatory agency's incentive expenditure while achieving $B \times 100$ percent improvement in environmental performance.

```
Data: Problem parameters $(c_R, c_q, \alpha, \delta, \eta_L, \eta_H, e, B)$ with
      $B \in [0, 1]$.
Result: If it exists, the value of the optimal incentive level, i.e.,
        $m_e^* > 0$, that provides a $B \times 100$ percent improvement in
        environmental performance at the minimum cost for
        the regulatory agency, and the induced decisions of the
        manufacturer, i.e., $p_R^*, p_\Delta^*(m_e^*)$ and $q_e^*(m_e^*)$.
Let $i = 0, m_e^* = 0, z_{EMP}^* = \infty$,
  $RHS_0 = e\left(D_H^R(p_R^*, p_\Delta^*(0), q_e^*(0)) + D_L^R(p_R^*, p_\Delta^*(0), q_e^*(0))\right) +$
  $(e - q_e)\left(D_H^G(p_R^*, p_\Delta^*(0), q_e^*(0)) + D_L^G(p_R^*, p_\Delta^*(0), q_e^*(0))\right)$,
  $\Pi_{M,0}^* = \Pi_M(p_R^*, p_\Delta^*(0), q_e^*(0))$;
/* $RHS_0$ is the total emissions with the
   manufacturer's optimal decisions when no
   incentive is offered by the regulatory
   agency.                                    */
while $i \leq 8$ do
    $i \leftarrow i + 1$;
    Solve problem $EMP_i$ when the $RHS$ of Constraint (2) (see
      Section 6) is equal to $RHS_0 \times (1 - B)$;
    if exists $m_e^{i^*}$ then
        if $m_e^{i^*}$ improves $\Pi_{M,0}^*$ under scenario i then
            if $z_i^*(m_e^{i^*}) < z_{EMP}^*$ then
                $m_e^* \leftarrow m_e^{i^*}$;
                $z_{EMP}^* \leftarrow z_i^*(m_e^{i^*})$;
/* A result of $m_e^* = 0$ implies that, under the
   given set of problem parameters, no positive
   incentive level enables the regulatory
   agency to attain the targeted $B \times 100\%$
   improvement in environmental performance. */
```

the demand source for the regular product is the low environmental awareness segment, the realized demand for the regular product is $\delta \times (1 - p_R^*) = 0.5 \times (1 - 0.5) = 0.25$. The observed demand composition results in an emissions level of $e \times 0.25 + (e - 0.4) \times 0.3 = 2.5 \times 0.25 + 2.1 \times 0.3 = 1.255$. In Fig. 5(b), with $\alpha = 0.75$ and when the regulatory agency does not impose a reduction target, the firm designs a green product with a greenness level of 0.35, and sets a price of $0.5 + 0.223 = 0.723$ for the green product. Because of the higher value of α, the optimal product design strategy of the manufacturer is to consider both segments in the design process, and eventually both segments purchase the green product, yielding the $L + H|\gtrless| \gtrless$ scenario with a total emissions of 1.240. We note that when $\alpha = 0.25$, 30%+25%=55% of the customers purchase the product's regular or green version; when $\alpha = 0.75$, 57.65% of customers purchase the green version. The change in the value of α from a lower value of 0.25 to a higher value of 0.75, results in (1) a slightly less green product ($q_e^*(0) = 0.4$ vs. 0.35) whose price is 9.6% lower (0.8 vs. 0.723), (2) 4.8% demand expansion (55% vs. 57.65%), (3) 9% increase in the manufacturer's profit (0.305 vs. 0.332), (4) 1.2% lower emissions (1.255 vs. 1.24), and (5) 7.2% improved social welfare (-0.7975 vs. -0.7400).

In Fig. 5, we study a problem instance with $\eta_L = \eta_H = 1$, implying that both consumer segments achieve full emission reduction efficiency in the use phase of the product (in Fig. 7, we will the discuss a case with $\eta_L < 1$). Regardless the α value of the low environmental awareness segment ($\alpha = 0.25$ or $\alpha = 0.75$), once a consumer in the low awareness level segment purchases the product, she or he fully achieves the intended emission reduction in the use phase of the product. A simple-to-use product with clearly communicated use-phase instructions may fall into this category. For such a product, the above example clearly illustrates the presence of an indirect incentive for the manufacturer: enhancing environmental awareness level of consumers can improve its profit while also positively shifting many performance indicators, even when no direct incentives are extended by the regulatory agency.

We now turn the regulatory agency's incentive design problem to achieve a targeted reduction in emissions. Fig. 5 reports changes in the values of the relevant performance indicators as the agency shifts its target from 0% to 7.5%. In the left column of Fig. 5 (Figs. 5(a) and 5(c)) we report the case with $\alpha = 0.25$, and in the right column (Figs. 5(b) and 5(d)) we present the case with $\alpha = 0.75$.

When $\alpha = 0.25$, even with a small reduction target such as 1%, the regulatory agency is forced to offer a substantially large incentive of $m_e = 2.16$. With this incentive, the manufacturer designs a product whose greenness level is $q_e^*(2.16) = 1.265$, significantly higher than the optimal greenness level when $m_e = 0$, i.e., $q_e^*(0) = 0.4$. The substantial increase in the greenness level of the green product is necessitated by the fact that the green product is purchased only by the high environmental awareness segment and, whilst expanding the demand with the increasing the greenness level of the green product, the manufacturer can start to reduce the emissions only when all customers of the high environmental segment have purchased the product and the demand expansion has pushed the demand to its upper limit of $(1 - \delta) \times 1 = 0.5$ under the $H|0|1$ scenario.

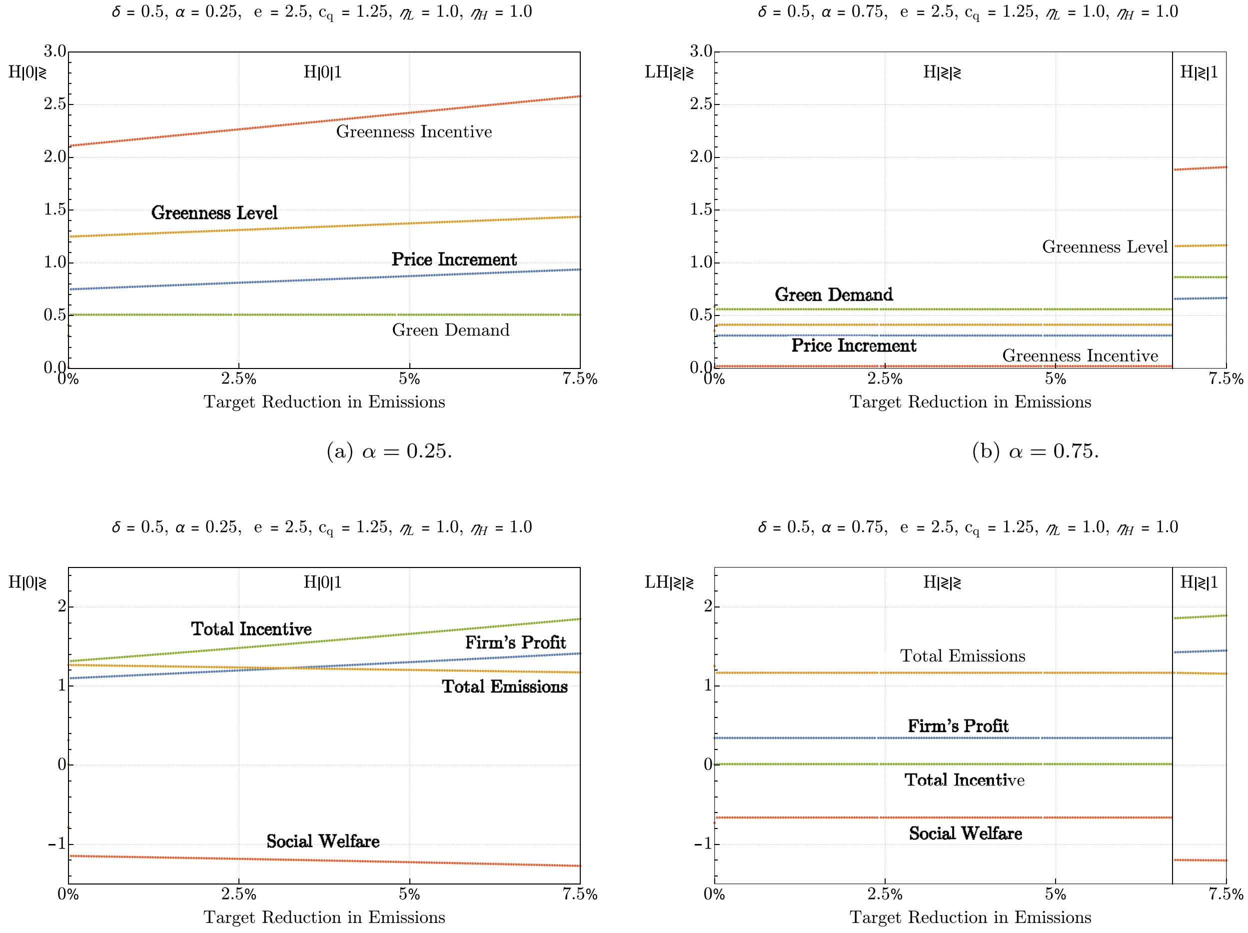
As illustrated in Fig. 5(a), when the targeted amount of emissions reduction increases, the manufacturer continues to increase the greenness level and the price of the green product. The resulting substantial profit gains of the manufacturer (Fig. 5(c)) decreases the social welfare at a rate that renders the incentive scheme an unjustifiable transfer of resources from the regulatory agency to the manufacturer. For example, when the target level is 5% reduction in emissions, social welfare decreases to -1.237 from its initial level of -0.7975.

The case of $\alpha = 0.75$ presents a more plausible context for the regulatory agency's incentive scheme to achieve a reduction in emissions. Fig. 5(b) reveals that a small incentive of $m_e = 0.012$ helps the manufacturer change its design strategy from $L + H|\gtrless| \gtrless$ to $H|\gtrless| \gtrless$ and the new green product with a greenness level of $q_e^*(0.012) = 0.405$ reduces the emissions by 6.7%. We note that even when the regulatory agency targets a smaller reduction level (e.g., 1%), its optimal strategy to minimize its total incentive expenditure is to offer an incentive of $m_e = 0.012$ resulting in a reduction of 6.7%. In the reduction target level range of $(0\%, 6.7\%]$, the price of the green product is $p_R^* + p_\Delta^*(0.012) = 0.5 + 0.302 = 0.802$, and the social welfare increases from -0.740 to -0.673 while the manufacturer's profit remains the same at 0.332. The source of reduction is the slight decrease in the demand for the green product (0.576 vs. 0.551) and lowered emissions level per product ($e - q_e^*(0) = 2.5 - 0.35 = 2.15$ vs. $e - q_e^*(0.012) = 2.5 - 0.405 = 2.095$).

The analysis of the figures presented Fig. 5 clearly reveals the impact of α, a critical parameter of our setting denoting the environmental awareness level of the low awareness segment of the market. When α is low, even when the use-phase efficiency of this segment is at its maximum level (i.e., $\eta_L = 1$), an attempt to reduce emissions via an incentive scheme simply transfers the resources of the regulatory agency to the manufacturer and results in a substantial social welfare loss. Therefore, when α is low, the efforts of the regulatory agency should be geared towards increasing the environmental awareness. For example, for a reduction target of 2.5%, the total incentive expenditure of the regulatory agency for $\alpha = 0.25$ and $\alpha = 0.75$ is 1.471 and 0.003, respectively. The difference can be viewed as an upper bound on the "cost" of efforts for educational initiatives, public awareness campaigns, social influence, and transparency about environmental practices through which α can be nudged to a higher level.

7.2. The impact of segment sizes

In Fig. 6, we study the impact of δ, a critical parameter of our setting that reflects the size of low environmental awareness segment,



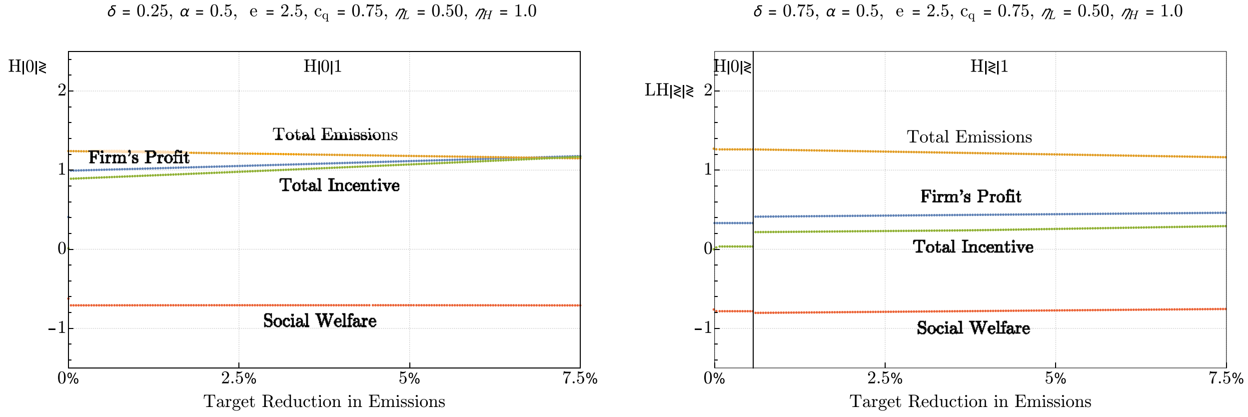
(a) $\alpha = 0.25$.

(b) $\alpha = 0.75$.

(c) $\alpha = 0.25$.

(d) $\alpha = 0.75$.

Fig. 5. Impact of the environmental awareness (α) level.



(a) $\delta = 0.25$.

(b) $\delta = 0.75$

Fig. 6. Impact of the segment sizes (δ).

on various performance indicators. In Fig. 6(a) we consider a problem setting with $\alpha = 0.5, \delta = 0.25, e = 2.5, c_q = 0.75, \eta_L = 0.5$ and $\eta_H = 1$. In Fig. 6(b) we simply set $\delta = 0.75$ without changing the remaining parameters.

We first discuss the $m_e = 0$ case to set the background for a comparison of the problem instances with $\delta = 0.25$ and $\delta = 0.75$. When the regulatory agency does not extend an incentive (i.e., $m_e = 0$) and $\delta = 0.25$ (0.75), we observe the following outcomes: the manufacturer's optimal strategy is $H|0|\gtrless$ ($L + H|\gtrless|\gtrless$), the greenness level of the product is 0.6666 (0.3125), the price of the green product is $0.5 + 0.5$ $(0.5 + 0.1953)$, the total demand for the regular and green products are $0.5 \times \delta = 0.5 \times 0.25 = 0.125$ and 0.5 (0 and 0.5651), respectively, the level of total emissions is 1.2291 (1.2574), the social welfare is −0.6354 (−0.7743), and the manufacturer makes a profit of 0.3958 (0.3193). When δ is larger, since there are more customers in the low environmental awareness segment, the manufacturer designs a cheaper and “less” green product that appeals to both segments. This results in lower social welfare and smaller profit for the manufacturer. The emissions level is higher only by 0.8%.

Let us now consider the case where the regulatory agency wants to reduce the emissions by 2.5%. When $\delta = 0.25$, the regulatory agency achieves its target with an incentive expenditure of 0.9678. With a larger low environmental awareness segment ($\delta = 0.75$), the regulatory agency can achieve the same objective of 2.5% reduction in emissions with a total expenditure of 0.2250. This observation may look counter-intuitive, however it is a direct result of the very high demand of the high environmental awareness segment in the case of $\delta = 0.25$ and $m_e = 0$. Note that when $\delta = 0.25$, 75% percent of the customers are in the high awareness segment and, when $m_e = 0$, $(0.5/0.75) \times 100 = 66.66\%$ of them purchase the green product. The only venue to reduce the emissions is to increase the greenness of the product. To reduce emissions, the regulatory agency covers the cost of further greening the product through its incentive scheme, and the total incentive expenditure of 0.9678 lowers the social welfare from -0.6354 to -0.7188. On the other hand, when $\delta = 0.75$, the manufacturer offers a more affordable green product that appeals both segments, and the regulatory agency can achieve a 2.5% reduction in emissions with a much lower incentive expenditure of 0.2250. Under the incentive scheme of the regulatory agency, the social welfare is now slightly lower (-0.7743 vs. -0.8025).

The analysis of the above two cases point to important dynamics in the management of emissions. Although the two cases feature low awareness segments that are considerably different in their sizes, the market dynamics (i.e., the decisions of the manufacturer and the consumers’ choices) results in comparable emissions in the absence of incentives: 1.2291 vs. 1.2574. When the regulatory agency steps in to reduce the emissions, the case of larger low awareness segment size offers more impact per unit incentive expenditure: $(1.2291 - 1.1982)/0.9678 = 0.0319$ vs. $(1.2574 - 1.225)/0.2250 = 0.144$. In summary, the model’s incentive mechanism aligns more effectively with market dynamics when the low awareness segment is larger.

7.3. The impact of use-phase efficiency

The discussion presented in Section 7.1 assumes that the consumers that are in the low awareness segment of the market are fully efficient in the use phase, i.e., through their use-phase behavior, they fully achieve the emissions reduction that the green product has been designed to deliver. As argued in Sections 2.2 and 3.1, use-phase behavior of consumers could lead to a divergence between the anticipated and realized reductions in the emissions of the green product, and this section’s goal is to understand the impact of this divergence on regulatory agency’s incentive expenditures.

In Fig. 7, we let $\delta = 0.5, e = 2.5$, $c_q = 1.25$, and $\eta_H = 1$, and study the interaction between the two critical parameters of the problem setting, i.e., η_L and α, with $\eta_L \in \{0.4, 0.6, 0.8, 1.0\}$ and $\alpha \in \{0.25, 0.50, 0.75\}$ (Figs. 7(a)–7(d)). The horizontal axes of the figures reflect the targeted level of emissions reduction, and the vertical axes report the total incentive the regulatory agency needs to offer to achieve the targeted level of emissions reduction.

When $\alpha = 0.25$, regardless the use-phase efficiency level of the of low awareness segment, i.e., η_L, only Scenario $H\,|0|\,1$ is observed. Although the two segments are of equal sizes ($\delta = 0.5$), due to the low value of α, the green product has minimal impact on the utility of the low environmental awareness segment, and the manufacturer can achieve target emissions reductions with a product that is designed for the high environmental awareness segment and purchased by every consumer in that segment (Scenario $H\,|0|\,1$). It is important to note that, because the low environmental awareness segment does not purchase the product, any cost incurred to improve their use-phase efficiency would have no return for the regulatory agency.

With $\alpha = 0.50$, the following scenario sequences are observed as the value of η_L changes: $\eta_L = 0.4 : H\,|0|\,1$; $\eta_L = 0.6 : H\,|{\gtrless}|\,1 \rightarrow H\,|0|\,1$; $\eta_L = 0.8 : H\,|{\gtrless}|\,{\gtrless} \rightarrow H\,|{\gtrless}|\,1 \rightarrow H\,|0|\,1$; $\eta_L = 1.0 : H\,|{\gtrless}|\,{\gtrless} \rightarrow H\,|{\gtrless}|\,1$. A comparison of the costs curves for $\alpha = 0.50$ across Fig. 7(a)–7(d) clearly reveals the positive impact of the higher η_L values on the total incentive expenditure the regulatory agency would incur to achieve a specific target emissions reduction. For example, for a target of 2.5% and η_L value of 0.4, the incentive expenditure is approximately 1.5. When η_L increases to 0.8, for the same target, the required expenditure decreases to 1.0. Furthermore, with an expenditure level of slightly higher than 1.0, the regulatory agency can target a reduction level of 5%.

Finally with $\alpha = 0.75$, because the green product’s impact on the utility of the low environmental awareness segment is relatively high, the green product is purchased by both segments, and the $H\,|{\gtrless}|\,{\gtrless} \rightarrow H\,|{\gtrless}|\,1$ Scenario sequence is observed for all η_L values. When the total incentive expenditures are compared, particularly for higher reduction targets (e.g., 7%) we observe that the regularly agency’s total expenditure level could be very high with lower η_L values.

These observations highlight the importance of having a higher value of α; when the environmental awareness level increases, even with relatively lower use-phase efficiency levels, incentive scheme turns out to be less costly for the regulatory agency. On the other hand, if the environmental awareness level is moderately high (e.g., $\alpha = 0.5$) yet difficult or costly to increase, an attempt to improve the use-phase efficiency can be used as an alternative instrument in reducing regulatory agency’s incentive expenditures. This analysis illustrates the value of jointly modeling consumer heterogeneity, use-phase behavior, firm response, and regulatory incentives. If use-phase efficiency were ignored, incentive design would rely on results that implicitly assume full compliance, leading to systematically sub-optimal policies. Only the integrated framework reveals how misjudging use-phase efficiency affects the magnitude of rebound effects and prevents regulatory agencies from achieving stated emissions targets.

7.4. The impact of manufacturing cost

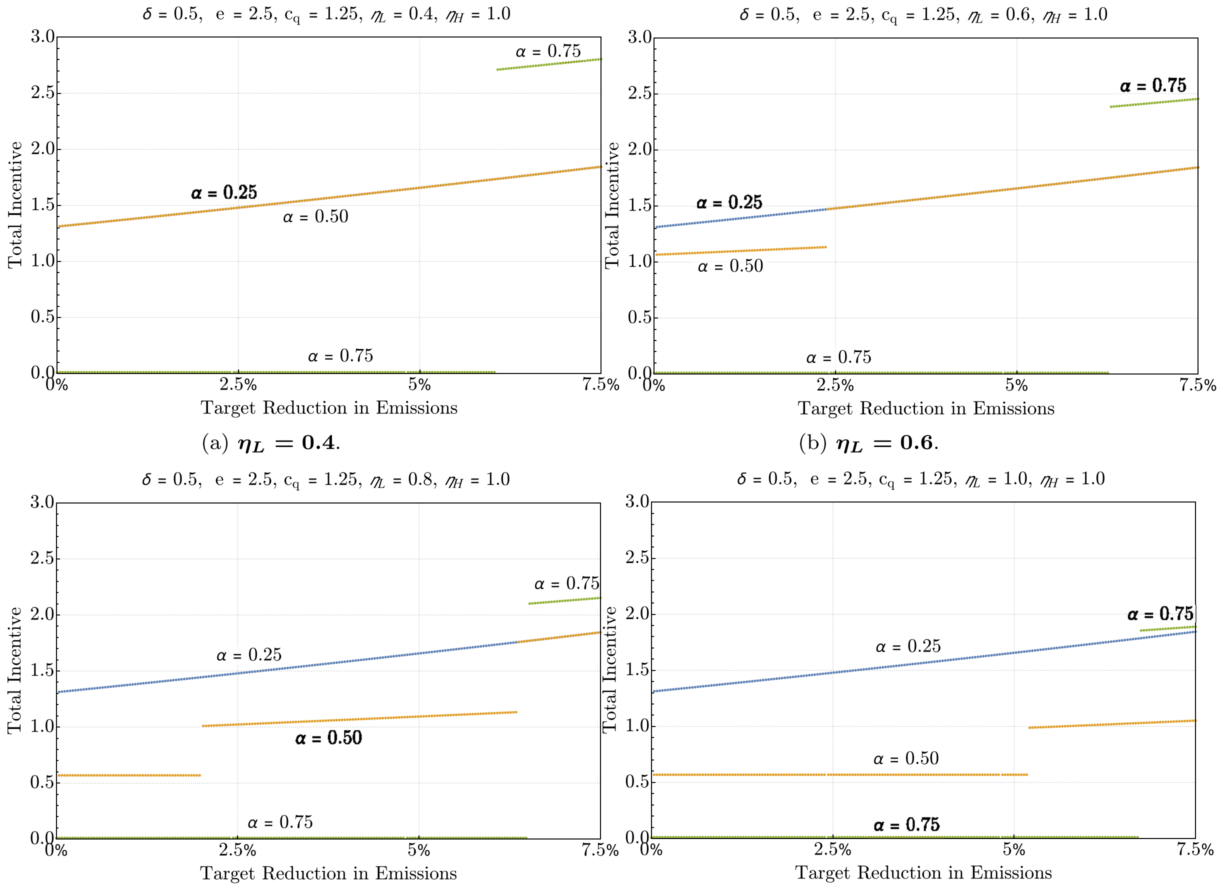
Per unit manufacturing cost of the green product, denoted by $c_q q_e^2$, is a quadratic function of its greenness level, and the parameter $c_q > 0$ is the coefficient that determines the steepness of the cost function. With a high c_q value, enhancing the greenness level of the product becomes more expensive and it is expected that regulatory agency will incur higher incentive expenditure as well.

In Fig. 8, we report the impact of c_q’s value on various performance indicators of interest. We consider a setting with $\delta = 0.5, e = 2.5$, $\eta_L = 0.75$, and $\eta_H = 1$, and study the interaction between the c_q and α parameters of the problem setting: 1) $c_q = 0.75$ and $\alpha \in \{0.25, 0.50, 0.75\}$ (Fig. 8(a)), and (2) $c_q = 1.25$ and $\alpha \in \{0.25, 0.50, 0.75\}$ (Fig. 8(b)).

As anticipated, with the higher value of c_q and particularly for $\alpha \in \{0.25, 0.50\}$, a comparison of Figs. 8(a) and 8(b) reveals that incentives would be much costlier for the regulatory agency. When $c_q = 1.25$ and $\alpha = 0.75$, we observe a setback that the higher c_q value imposes: although the regulatory agency can achieve its objective with a minimal expenditure when the targeted emissions reduction is in the $(0\%, 6.44\%]$ range, the total incentive expenditure jumps to a much higher level as soon as the target is set above the threshold value of 6.45%. As it has been the case in Sections 7.1 and 7.3, the parameter α is a critical moderating factor for the regulatory agency’s incentive expenditures.

7.5. Practical implementation and parameter mapping

To facilitate application beyond the illustrative detergent setting, we outline a calibration roadmap and clarify what typically differs across industries. A regulator (or practitioner) can first select the focal EPI and measure the baseline impact $EI(0)$ and the impact of candidate green designs $EI(q_e)$ using life-cycle assessment data or environmental product declarations mapped to the EPI. Demand-side parameters,



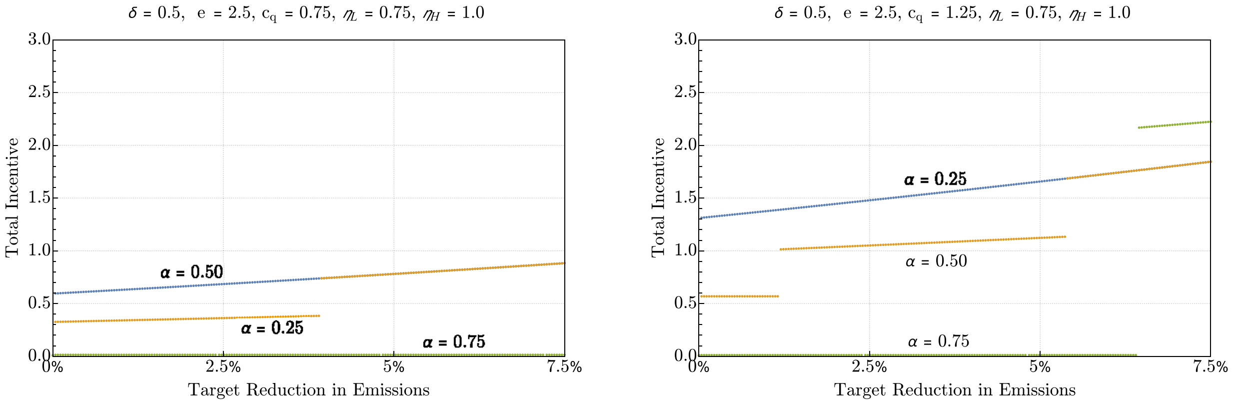
(a) $\boldsymbol{\eta_L = 0.4}$.

(b) $\boldsymbol{\eta_L = 0.6}$.

(c) $\boldsymbol{\eta_L = 0.8}$.

(d) $\boldsymbol{\eta_L = 1.0}$.

Fig. 7. Impact of the use-phase efficiency of the low awareness segment (η_L).



(a) $c_q = 0.75$.

(b) $c_q = 1.25$.

Fig. 8. Impact of the greenness level cost coefficient (c_q).

including segment size δ and awareness-related parameters (e.g., α), can be inferred from price-share data, survey-based segmentation, or discrete-choice/conjoint evidence that identifies willingness-to-pay for greenness across consumer groups. The greening-cost coefficient c_q can be approximated from engineering cost curves, supplier information, marginal abatement cost data, or observed cost changes associated with past design upgrades.

Use-phase efficiency parameters (η_L, η_H) can be calculated from field-use evidence when available; when such data are unavailable, product-category-specific surveys may provide proxies. The interpretation of η is category-dependent: for cleaning products it reflects usage intensity (e.g., dosing deviations), for energy-using durables it relates to operating conditions and settings, and for long-life-cycle products it may be proxied by realized lifetime, maintenance, or repair behavior. When point estimates are not available, the framework can be evaluated over empirically plausible parameter ranges. Given calibrated inputs, the model can then be solved to compute equilibrium price-greenness responses and identify the incentive level that achieves a targeted emissions-reduction objective under the relevant market conditions.

8. Conclusions

In this paper, we present a framework that incorporates a rational consumer response model into a firm's product line design and pricing strategies. The firm operates in a market where customers have heterogeneous product valuations and varying sensitivity to products' environmental impacts. This framework is further extended to include an incentive mechanism introduced by regulatory agencies to promote sustainability goals, such as targeted emission reductions. Additionally, we analyze how consumer behavior during the use phase of green products affects key performance metrics. Through this framework, we seek to explore the interaction between regulatory incentives and real-world consumer behavior. Our study examines the impact of market heterogeneity on product line design and pricing, the role of regulatory incentives in shaping green product development, and how consumer usage patterns influence both green product design decisions and regulatory incentive structures.

Through an experimental study the paper first provides support for the hypothesis that a product's "greenness" can significantly enhance consumers' willingness-to-pay values. The findings of the experiment also demonstrate that the extent of this effect differs based on consumers' environmental awareness levels. The findings suggest the existence of distinct consumer segments that respond differently to product greenness, emphasizing the need for targeted strategies in product line design.

A model is then developed to solve the product line design and pricing problems faced by a manufacturer in a market comprising two consumer segments, each with differing environmental awareness levels and, consequently, varying product valuations. The model also includes a critical "incentive" component, which is a sustainability-driven financial reward that the regulatory agency can offer to the manufacturer. This incentive is structured as a "monetary unit"/ "unit improvement in an environmental performance indicator per product", such as "USD"/ "unit of reduced emissions per product".

Using an experimental study and computational analyses derived from the stylized model, this paper provides a unified framework to address the incentive design problem faced by regulatory agencies. The framework contributes the literature by offering an analytical approach to evaluating trade-offs in sustainability management. It enables regulatory agencies to systematically assess the cost-effectiveness of incentives for green products or programs aimed at improving consumers' use-phase efficiency under diverse market conditions.

Section 7 highlights the scenarios where the regulatory agency's resources would be most effective in achieving its goal of reducing emissions: (1) Higher levels of environmental awareness have a substantial impact on the effectiveness of incentive mechanisms designed to reduce emissions. The analysis indicates that as environmental awareness increases, regulatory agencies can achieve emission reduction targets more efficiently, with lower associated incentive costs. As a result, leveraging the market dynamics associated with higher levels of environmental awareness presents an opportunity to enhance the cost-effectiveness of sustainability incentives. Thus, increasing environmental awareness serves as a complementary strategy for optimizing the efficiency of these incentives. (2) The analysis further demonstrates that as the low-awareness segment increases in size, the reductions in emissions per unit of incentive expenditure become more substantial. This result underscores the critical role of understanding segment sizes in optimizing the allocation of regulatory agencies' resources to incentive schemes designed to promote green products across various product categories. (3) When consumers in the low-awareness segment fail to use green products efficiently during the use phase, the regulatory agency's costs for meeting its emission reduction targets rise. The analysis indicates that enhancing use-phase efficiency can substantially lower the regulatory agency's incentive expenditures. (4) The computational analysis also illustrates that as the cost of greening a product increases, the regulatory agency's expenditures also rise, especially when targeting emissions reductions beyond a certain threshold. The qualitative insights regarding incentive calibration, rebound effects, and optimal greenness decisions are robust to alternative interpretations of m_e as either a subsidy-type mechanism or a fee-modulation instrument, provided that it operates as a marginal, performance-linked adjustment to the firm's effective cost or revenue structure.

While the mechanisms analyzed in this study are relevant to policy agendas that emphasize sustainable production and consumption (e.g., SDG 12), the model does not capture long-run innovation dynamics, structural industry transformation, or broader sustainability transitions (e.g., SDG 9). The results identify an operational channel through which incentive programs can influence equilibrium design and adoption outcomes. They should therefore be interpreted as equilibrium insights within the specified product and market setting, rather than as predictions about long-term technological change or macro-level sustainability outcomes.

While our main analysis adopts a linear environmental-utility structure that reflects single-unit purchase behavior with no repeat buying, our robustness extension (Appendix F) demonstrates that incorporating nonlinear perception of greenness (i.e., capturing diminishing or amplifying sensitivity) produces consistent qualitative outcomes. Thus, the linear case serves as a benchmark for future studies exploring repeat consumption or dynamic purchasing behaviors where nonlinear structures are empirically relevant.

From a methodological standpoint, our framework provides a rigorous analytical foundation upon which more data-intensive or empirically calibrated analyses of sustainable product design and policy interaction can be developed in future research. The primary limitations of the model presented in this paper are (1) the assumption of a uniform demand distribution, (2) the specific structure of the incentive mechanism and (3) its focus on products with relatively high environmental impact in the use phase. There are incentive mechanisms where regulatory agencies offer incentives directly to consumers, such as the "Clean Vehicle Credits" provided by the US government [61]. Developing models for products with lower use-phase environmental impact and with different functional forms for demand distributions or alternative incentive mechanisms would be valuable extensions of the current model. Future research could extend this framework to other product categories with measurable use-phase variation, using empirical calibration to assess industry-specific design, pricing, and policy implications. In addition, our solution approach evaluates all demand cases arising from two consumer segments and two product tiers; in settings with additional tiers or segments, the regulator's problem can be formulated as a bi-level program in which the upper level captures the regulator's policy choice and the lower level the firm's response. Extending the model and developing scalable solution methods for such higher-dimensional formulations constitute promising directions for future research.

CRediT authorship contribution statement

Selçuk Karabatı: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Burak Gökgür:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Güneş Biliciler:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.omega.2026.103573.

Data availability

The following statement is included in the manuscript: "The data file for the experiment is available at: https://osf.io/vme73?view_only=701385ffaf1e41ceb64f737b3a50092c".

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