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Towards Reuse: The Implications of Price Incentives and Convenience of Reusable Packaging

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Abstract

Problem Definition: Growing environmental awareness is prompting consumers to consider reusable alternatives to disposable packaging, driving firms in the takeaway food and beverage sector to explore reusable packaging models. In addition to encouraging consumers to use their personal reusable packaging, some firms now offer firm-owned reusable packaging as an alternative reuse option. This paper examines how price incentives and convenience enhancements shape consumers' packaging choices and the resulting environmental and profitability implications of reusable packaging models.

Methodology/Results: Using a game-theoretical model, we analyze a firm's pricing and reuse-program decisions when consumers choose among disposable packaging, consumer-owned reusable packaging, and firm-owned reusable packaging. Our key findings are as follows. First, a more eco-conscious market does not necessarily strengthen the firm's incentive to introduce a firm-owned reusable packaging program. When disposable packaging is inexpensive, the program's main value lies in price discrimination rather than market expansion; as the market becomes more eco-conscious, this price-discrimination benefit weakens. Second, when disposable packaging is costly, the introduction of firm-owned reusable packaging can increase packaging waste, as the firm may strategically reduce the price discount for consumer-owned reuse. Finally, convenience improvements have asymmetric effects. Improving the convenience of consumer-owned reuse generally reduces packaging waste. However, making the return process more convenient for firm-owned reuse can increase packaging waste by shifting some consumers from consumer-owned to firm-owned reuse, which remains subject to non-return risk.

Managerial Implications: Firms in the takeaway food and beverage sector should jointly manage firm-owned and consumer-owned reusable packaging. Price incentives and convenience design should be evaluated based on how they shift consumers across packaging options and affect the tension between firm profitability and packaging waste reduction.

Keywords: Reusable packaging, price incentives, convenience, consumer pro-environmental behavior, sustainability

1 Introduction

Single-use packaging is widely used due to its cost-effectiveness and convenience. However, it significantly contributes to global plastic pollution. Alarmingly, only 14% of plastic packaging globally is recycled, with the majority ending up in landfills or polluting oceans and waterways (Ellen Macarthur Foundation, 2020). Therefore, according to the United Nations Environment Programme, reuse is believed to be the most powerful solution to tackle plastic pollution. For instance, reusing just 10% of plastic products could prevent nearly half of all plastic waste from entering the ocean (Ingilizian, 2021). Over 500 organizations have endorsed the New Plastics Economy Global Commitment, emphasizing the importance of adopting reuse models to address single-use packaging waste (UN Environment Programme, 2022). However, the challenge lies in understanding how companies can effectively transition from single-use packaging to reusable packaging models.

Consumer engagement is fundamental to the success of reusable packaging models. A 2021 World Economic Forum survey revealed that 59% of global consumers expressed interest in adopting reusable packaging, primarily motivated by the desire to mitigate the environmental harms of disposable waste (Wood, 2021). Despite this interest, there is a significant gap between intention and action. A recent survey found that while 80% of respondents aimed to reduce single-use packaging, only 22% actively used reusable packaging (PA Consulting, 2024). This intention-action gap is largely attributed to two barriers. First, many consumers lack immediate access to their personal reusable containers when they decide to go shopping, as they often forget to bring them (Benveniste, 2024). Second, even when such containers are immediately available, using them often involves inconvenience. Addressing these barriers requires companies to implement targeted measures to foster greater participation in reusable packaging models.

Currently, the most common and straightforward strategy employed by firms is offering price incentives to encourage consumers to use personal reusable packaging. This approach has two key benefits. First, it helps consumers offset the inconvenience of using reusable packaging. Second, it allows firms to maintain their existing operations without significant changes while saving on packaging costs by not providing disposable alternatives. As a result, this strategy has been widely adopted in the takeaway food and beverage sector. For example, since 1985, Starbucks has been offering a $0.10 discount in the U.S. to customers who bring their own reusable cups, and the program is still ongoing in 2025 (Starbucks, 2020, 2025). Similar to Starbucks, many other big chain coffee shops, including Pret, Costa, Caffè Nero, have offered price incentives to encourage consumer-owned reusable cups as a commitment to reducing disposable packaging (Mata, 2025).

In order to further incentivize the uptake of reusable packaging, some companies have initiated pilot programs allowing consumers to borrow firm-owned reusable packaging. For example, through its "Borrow a Cup" pilot program, Starbucks allows consumers to either bring their own personal cup or borrow a reusable cup provided by the company (Starbucks, 2023). If consumers choose to borrow Starbucks' reusable cup, they need to pay a deposit, which can be refunded when the cup is returned to Starbucks stores. The deposit return scheme is designed to incentivize the return of reusable packaging, as some firm-owned packaging may go unreturned (Packaging Europe, 2025). Starbucks collects these cups daily, professionally cleans and sanitizes them using commercial dish-washing equipment, and reintroduces them into circulation within 48 hours. Similarly, since 2022, Costa Coffee has started to run a trial of a returnable cup scheme as an additional reuse option for consumers who do not take a personal reusable cup (Costa, 2024). The availability of firm-owned reusable packaging ensures that a reusable option is accessible to all consumers. However, many still find it inconvenient to use, as it requires returning the packaging to the store. Therefore, firms also offer price incentives to encourage the use of firm-owned reusable packaging (Starbucks, 2023).

In addition to price incentives, improving convenience is considered essential for promoting the adoption of reusable packaging, whether consumer-owned or firm-owned. For example, since cleaning is a major inconvenience associated with consumer-owned reusable packaging, firms could install washing stations in stores to reduce this burden for consumers (Yonhap, 2024). Similarly, to streamline the return process for firm-owned reusable packaging, companies could introduce more flexible return options, such as home collection services (Ridwell, 2021). However, because firms can also offer price incentives to compensate for inconvenience, the interaction between price incentives and convenience improvements introduces complexity to their overall impact on firm profitability and reusable packaging adoption. To make matters even more complicated, in addition to offering price discounts alone, firms typically have flexibility in setting their menu prices alongside their reusable packaging programs. For example, in the Chinese market, Starbucks raised coffee prices by 1 yuan in 2018 when they increased the price discount for customer-owned reusable cups from 3 yuan to 4 yuan (Zhang, 2018).

In this paper, we examine the complex pricing problem faced by a profit-maximizing firm in the takeaway food and beverage sector, where consumers can choose among disposable packaging, personal reusable packaging, and firm-owned reusable packaging. Our goal is to investigate the economic and environmental implications of offering firm-owned reusable packaging and improving the convenience associated with reusable options, whether personal or firm-owned.

To address these questions, we develop a game-theoretical model that captures the strategic interactions between a firm and its customers, who differ in their environmental preferences and immediate access to personal reusable packaging. The main findings are as follows. First, a more eco-conscious market does not necessarily strengthen the firm's incentive to introduce a firm-owned reusable packaging program. When disposable packaging is inexpensive, the firm can already attract both eco-conscious and eco-unconscious consumers by setting a relatively low price, so firm-owned reusable packaging adds little through market expansion. Instead, its main business value is to support price discrimination: the firm can raise the disposable-packaging price and earn more from eco-unconscious consumers who continue to choose disposables. As the market becomes more eco-conscious, this group shrinks, weakening the price-discrimination benefit and potentially making firm-owned reusable packaging less attractive to the firm. Second, when disposable packaging is costly to offer, as may occur under regulations such as plastic taxes and extended producer responsibility requirements (Cartwright, 2025), introducing firm-owned reusable packaging can help the firm reduce the discount offered for consumer-owned reuse and save on incentive costs. However, such a reduction in price incentives can lead to more packaging waste, as the reduced discount discourages some eco-unconscious consumers from continuing to use consumer-owned reusable packaging and prompts them to switch to disposable options. Finally, improving the convenience of personal reusable packaging generally leads to a win–win outcome, increasing firm profit while reducing packaging waste. In contrast, improving the return convenience of firm-owned reusable packaging may unexpectedly increase packaging waste. This occurs because some consumers may switch from the consumer-owned option to the firm-owned option, but not all return the borrowed packaging, which leads to more packaging waste.

2 Related Literature

There are two streams of literature particularly relevant to this research: sustainable operations with eco-conscious consumers and the operations of circular business models. We review each stream separately and position our paper accordingly.

Consumers' environmental concerns significantly influence their willingness-to-pay for products, a phenomenon observed across various industries (e.g., Laroche et al. 2001; Lanz et al. 2018). Therefore, a growing body of sustainable operations literature has explicitly incorporated consumer environmental preference in different contexts, such as product design (Bertini et al., 2022) and carbon offsetting (Gao and Souza, 2022). These studies assume that eco-conscious consumers experience a

disutility from purchasing the product due to its environmental impact, which motivates firms to implement emission reduction strategies. Our paper focuses on the environmental impact of product packaging, which has been empirically shown as a key factor affecting eco-conscious consumers' purchasing decisions (Rokka and Uusitalo, 2008). Specifically, we study the effectiveness of reusable packaging strategy in the presence of eco-conscious consumers.

Consumers' environmental concerns drive their engagement in pro-environmental behaviors, which involve reducing environmental impact and resource consumption throughout a product's life cycle, such as sustainable disposal and the reuse of products or packaging (White et al., 2019). The intrinsic motivation of pro-environmental behavior can be explained by the "cold prickle" effect (Andreoni, 1995; Adams et al., 2020). Specifically, eco-conscious consumers will feel negative emotions, such as guilt and anxiety, when failing to engage in pro-environmental behavior since they are aware of the resulting environmental impact and feel responsible for their actions. Although consumer pro-environmental behavior has garnered significantly more interest in marketing (White et al., 2019), research on its impact in operations remains limited. Huang et al. (2024) explicitly model consumers' decisions on engagement in recycling behavior and analytically examine its impact on the operations of closed-loop supply chains. Our research advances this stream by examining another type of pro-environmental behavior: using reusable packaging instead of disposable packaging when purchasing a product. Additionally, we consider overall reuse adoption among consumers as a key performance indicator of the firm's social responsibility, enabling us to generate insights into why and how a profit-maximizing firm should promote this behavior.

The circular economy has received growing attention from both academia and industry (Agrawal et al., 2019). A stream of research analyzes the operations of various circular business models, such as product servitization (Örsdemir et al., 2019; Sun et al., 2024), recycling (Saragih et al., 2024), and upcycling (Long and Gui, 2024). In this paper, we focus on the reusable packaging model, a critical component of the circular economy. Reusable packaging has been proven to be more environmentally friendly than single-use packaging (Coelho et al., 2020). According to Greenwood et al. (2021), reusable packaging systems can be categorized into two models: (1) consumer-owned reusable packaging, where consumers use their personal reusable packaging to refill the product, and (2) firm-owned reusable packaging, where firms provide the reusable packaging such that consumers can borrow and return it after each use. Recently, some papers have paid attention to the impact of consumers' adoption of personal reusable packaging on operational decisions. For example, Aydinliyim and Pangburn (2012) analyze the pricing strategy when a firm offers a reduced-packaging option for

its product. Kirci et al. (2023) study the impact of unpackaged sales, where consumers can choose to buy products in a loose format (without packaging), on a firm's profit and the resulting food waste. In contrast to these studies, our paper develops a unified framework to analyze the joint implementation of consumer-owned and firm-owned reusable packaging systems and examines its impact on packaging waste.

Our paper is most closely related to Peng et al. (2025), as both studies examine firms' sustainable packaging operations in the presence of eco-conscious consumers. However, the two studies address fundamentally different decision problems. First, Peng et al. (2025) examines how a firm should communicate and verify the greenness of its disposable packaging. In their setting, consumer-owned reuse, referred to as Bring-Your-Own-Container (BYOC), serves as a transparent sustainable option, and consumers engage in BYOC primarily when they distrust the firm's green claims. In contrast, our study shifts the focus from information asymmetry in green claims to operational challenges arising when consumer-owned reuse coexists with a firm-owned reusable packaging program. By explicitly modeling uncertainty in the return process, we capture a distinctive operational friction that is absent from prior work, namely the non-return risk associated with firm-owned reusable packaging. Second, reflecting these differences in research focus, the main drivers of results also differ across the two studies. In Peng et al. (2025), outcomes are driven by consumers' perceptions of green claims and the resulting shifts in choice between disposable packaging and BYOC. In contrast, our results are driven by firms' pricing and convenience decisions for the two reusable packaging options, consumer-owned and firm-owned, which generate substitution dynamics between them. This, in turn, allows us to uncover a new mechanism whereby a firm-owned option can displace consumer-owned reuse and increase packaging waste due to non-return.

3 Benchmark Model Without Firm-Owned Reusable Packaging

We consider a firm in the takeaway food and beverage sector, such as a coffee shop, where consumer-owned reusable packaging and firm-owned reusable packaging are both feasible in practice and can coexist as direct substitutes for disposable packaging.[1] In this section, we first analyze the benchmark case in which the firm provides disposable packaging and consumers may use their own reusable packaging, while firm-owned reusable packaging is not yet available.

[1] In many other packaged food sectors, only one reuse model is typically viable, limiting the applicability of our framework. Nonetheless, our results extend to other packaged food contexts where all three options are feasible.

3.1 Model Description

The firm sells a single product (e.g., coffee) in the market. Each product must be delivered to consumers in packaging (e.g., coffee cups). The firm provides only disposable packaging, with a unit cost of $c_d > 0$. In addition to the firm's disposable packaging, consumers could also choose to use their personal reusable packaging (i.e., consumer-owned reusable packaging). For ease of exposition, we have normalized the production cost of the main product (e.g., the coffee) to zero.

Without loss of generality, we normalize the market size to one. Let v represent consumers' valuation of the main product (e.g., coffee). The product packaging does not generate additional value for consumers; however, its environmental performance can influence consumers' purchase decisions and packaging choices. Our model incorporates two dimensions of consumer heterogeneity related to the product packaging. First, consumers differ in their environmental preferences. Specifically, a fraction $\alpha \in (0, 1)$ of the population consists of *eco-conscious* consumers, who are environmentally aware and incur a disutility $\xi > 0$ from generating packaging waste[2]. This disutility may stem from a sense of guilt (or a "cold prickle") associated with the substantial environmental impact of packaging waste (Andreoni, 1995; Bertini et al., 2022). The remaining $1-\alpha$ are *eco-unconscious* consumers, who lack environmental awareness and therefore do not experience such disutility. Second, consumers differ in the situational availability of their personal reusable packaging at the time of purchase (Putnam-Farr et al., 2023; PA Consulting, 2024). A portion $\theta \in (0, 1)$, referred to as *packaging-independent* consumers, has personal reusable packaging immediately accessible and can directly choose between reusable and disposable packaging. The remaining $1 - \theta$, known as *packaging-dependent* consumers, do not have their reusable packaging immediately accessible (e.g., it may be left at home or at the office). Consequently, these consumers must incur an additional hassle cost $k > 0$ to retrieve it if they wish to use their reusable packaging. The parameter k captures the extra effort and time associated with this lack of immediate access. Hereafter, we refer to k as the packaging retrieval cost. Note that packaging-dependent consumers will retrieve their personal reusable packaging if and only if they decide to use it to purchase the product. Therefore, if they opt for disposable packaging, they will not retrieve their personal reusable packaging.

One remark about the demand model: While consumers may be heterogeneous in various aspects, this paper focuses on their environmental preferences and personal reusable packaging availability, both of which are of significant importance in the discussion of reusable packaging. In particular,

[2]In practice, eco-conscious consumers may exhibit heterogeneity in their environmental disutility. To account for this possibility, we consider an extension in which ξ follows a general distribution. We show that our main results remain robust to this extension. Please refer to Online Supplement III for details.

we have assumed consumers have a homogeneous base valuation for the product, v. This approach, with homogeneous base valuation and heterogeneous preference for product's green/responsibility attributes, is consistent with most literature in the field of sustainable operations management (e.g., Guo et al. (2016); Lin et al. (2020)). Adding another dimension of consumer heterogeneity, such as heterogeneous product valuation v, can significantly complicate the analysis; however, it will not alter the underlying mechanism or driving force behind the main results, especially given that the base valuation v does not affect consumers' choice between different types of packaging. Please refer to Online Supplement II for the details regarding the model extension with heterogeneous consumer valuations.

As a result, there are four types of consumers in the market: type-CI, type-CD, type-UI, and type-UD, where C/U indicates eco-conscious/eco-unconscious consumers and I/D indicates packaging-independent/packaging-dependent consumers. Compared to disposable packaging, utilizing personal reusable packaging involves inherent inconvenience, regardless of whether consumers need to make an effort to retrieve it. For example, consumers need to wash it before purchase to ensure it is sanitary for refilling. We let $h_c > 0$ denote this inherent usage hassle (e.g., cleaning and carrying) that all consumers incur when using personal reusable packaging.[3] Furthermore, when choosing disposable packaging, eco-conscious consumers incur the disutility ξ, since it generates packaging waste; in contrast, when using personal reusable packaging, they do not incur this disutility, as this option does not generate packaging waste.

To promote the adoption of reusable packaging, firms in practice typically offer different prices for disposable packaging p_d and consumer-owned reusable packaging p_c, where $p_c \leq p_d$ reflects the price incentives to help consumers overcome the hassle of using reusable packaging.[4] To keep the demand functions concise, we use type-specific notation. Let M_j denote the segment size of type-j consumers. Let K_j denote the packaging retrieval cost incurred by type-j consumers when using consumer-owned reusable packaging: $K_j = 0$ for packaging-independent consumers and $K_j = k$ for packaging-dependent consumers. Let Ξ_j denote the environmental disutility incurred by type-j consumers when using disposable packaging: $\Xi_j = \xi$ for eco-conscious consumers and $\Xi_j = 0$

[3]The model can be readily extended to allow for different hassle costs between the eco-conscious and eco-unconscious consumers. Let eco-conscious consumers' hassle cost remain h_c. For eco-unconscious consumers, suppose their hassle cost is $h_c + a$, where $a > 0$, reflecting the idea that eco-conscious consumers, due to their environmental preferences, find it less burdensome to carry or clean their personal reusable containers. In Online Appendix I, we show that the equilibrium outcomes with and without firm-owned reusable packaging remain largely unchanged if consumer's packaging retrieval cost k exceeds the additional hassle cost a for eco-unconscious consumers, and thus our main results continue to hold.

[4]In practice, eco-conscious consumers may be less responsive to price incentives than eco-unconscious consumers due to crowding-out effect. Please refer to Online Supplement I for the detailed discussion about the implication of crowding-out effect.

Table 1: Consumer Types and Type-Specific Heterogeneity

Consumer type j	Segment size M_j	Packaging retrieval cost K_j	Environmental disutility Ξ_j
CI	$\alpha\theta$	0	ξ
CD	$\alpha(1-\theta)$	k	ξ
UI	$(1-\alpha)\theta$	0	0
UD	$(1-\alpha)(1-\theta)$	k	0

for eco-unconscious consumers. These values are summarized in Table 1. For each consumer type $j \in \{CI, CD, UI, UD\}$, we define two utilities. First, $u_{D,j}$ denotes type-j consumers' utility from purchasing the product at price p_d with disposable packaging. Second, $u_{C,j}$ denotes type-j consumers' utility from purchasing the product at price p_c with consumer-owned reusable packaging. Based on Table 1, these utilities are

$$u_{D,j} = v - p_d - \Xi_j, \qquad u_{C,j} = v - p_c - h_c - K_j. \tag{1}$$

Consumers make a purchase if and only if their utility is non-negative and choose the packaging type that maximizes their utility. Specifically, each consumer type prefers consumer-owned reusable packaging to disposable packaging only if the price discount, $p_d - p_c$, exceeds a certain threshold $h_c - \Xi_j + K_j$. Since $\xi > 0$ and $k > 0$, eco-conscious consumers require a smaller discount than eco-unconscious consumers, and consumers without initial access to a reusable container require a larger discount than those with access.

The interaction between consumers and the firm can be modeled as a sequential game. First, the firm sets the product prices p_d and p_c, corresponding to disposable packaging and consumer-owned reusable packaging, respectively. Second, consumers make the purchase decision with packaging choice to maximize their utility. Given the utility functions above, we can identify which packaging option is chosen by each consumer segment $j \in \{CI, UI, CD, UD\}$. Because consumers within the same segment face the same utility comparison, a segment either chooses a given packaging option in full or does not choose it. Accordingly, $d_{D,j}$ and $d_{C,j}$ denote the segment-level demands for disposable packaging and consumer-owned reusable packaging, respectively. In the expressions below, demand equals the size of segment j when the stated conditions hold and equals zero otherwise, where the first condition ensures non-negative utility, and the second ensures that the corresponding packaging option maximizes consumers' utility:[5]

[5]When consumers are indifferent among multiple packaging options, we break ties in favor of the option that yields higher profit for the firm. This tie-breaking rule is reflected in the specification of the demand conditions.

- For $j \in \{CI, CD\}$,

$$d_{D,j} = M_j \qquad \text{if } p_d \leq v - \xi \text{ and } p_d < p_c + h_c + K_j - \xi, \tag{2}$$

$$d_{C,j} = M_j \qquad \text{if } p_c \leq v - h_c - K_j \text{ and } p_c \leq p_d + \xi - h_c - K_j. \tag{3}$$

- For $j \in \{UI, UD\}$,

$$d_{D,j} = M_j \qquad \text{if } p_d \leq v \text{ and } p_d \leq p_c + h_c + K_j, \tag{4}$$

$$d_{C,j} = M_j \qquad \text{if } p_c \leq v - h_c - K_j \text{ and } p_c < p_d - h_c - K_j. \tag{5}$$

Then, the total numbers of consumers who use the firm's disposable packaging, denoted by d_D, and who use their personal reusable packaging, denoted by d_C, are given by

$$d_D = \sum_{j \in \{CI, CD, UI, UD\}} d_{D,j}, \tag{6}$$

$$d_C = \sum_{j \in \{CI, CD, UI, UD\}} d_{C,j}. \tag{7}$$

Note that consumers who use personal reusable packaging help the firm save the disposable packaging cost c_d. Therefore, given the demand functions, the firm's profit function is

$$\pi(p_d, p_c) = (p_d - c_d) d_D + p_c d_C, \tag{8}$$

where $p_d - c_d$ is the marginal profit if consumers use the firm-owned disposable packaging, and p_c is the marginal profit when consumers use their personal reusable packaging.

3.2 Equilibrium Analysis

We use superscript $(\cdot)^b$ to denote the equilibrium outcome in the benchmark model. Proofs of all the results in the main model are given in Online Appendix IV. Appendix A summarized all the notations. Note that encouraging the adoption of consumer-owned reusable packaging may generate two potential benefits: (i) attracting eco-conscious consumers and (ii) saving packaging costs. To capture the fact that most firms consider sustainability due to the changing market preference toward the environment, rather than merely as a cost-saving move, we assume that the cost of disposable packaging is not very high (which is generally true in practice (RSM UK, 2023)), so the firm is willing to incentivize the use of consumer-owned reusable packaging only if there are some eco-conscious consumers in the market. As shown in the following lemma, this means $c_d < h_c$.

Lemma 1. *If there are no eco-conscious consumers in the market (i.e., $\alpha = 0$), then there are no*

customers who are incentivized to use reusable packaging in equilibrium (i.e., $d_C^b = 0$) if and only if the cost of disposable packaging is low (i.e., $c_d < h_c$).

Next, we discuss the firm's optimal pricing strategy. Note that by setting the two prices, p_d and p_c with $p_c \leq p_d$, the firm implicitly determines the price discount for consumer-owned reusable packaging, given by $p_d - p_c$.

Lemma 2. *In the benchmark model, there exist threshold functions $\mathcal{C}_1^b(v, \alpha, \theta, h_c, \xi, k)$ and $\mathcal{C}_2^b(v, \alpha, \theta, h_c, \xi, k)$ such that:*

(i) If $c_d \leq \min((h_c - \xi)^+, \mathcal{C}_1^b(\cdot))$, then $p_d^b = v - \xi$, $p_c^b = v - \xi$.

(ii) If $(h_c - \xi)^+ < c_d \leq \mathcal{C}_1^b(\cdot)$, then $p_d^b = v - \xi$, $p_c^b = v - \max(\xi, h_c)$.

(iii) If $\mathcal{C}_1^b(\cdot) < c_d \leq \mathcal{C}_2^b(\cdot)$ and $k < \min(\alpha(1-\theta)(v - h_c), \xi)$, then $p_d^b = v - k$, $p_c^b = v - h_c - k$.

(iv) If $\mathcal{C}_1^b(\cdot) < c_d \leq \mathcal{C}_2^b(\cdot)$ and $k \geq \min(\alpha(1-\theta)(v - h_c), \xi)$, then $p_d^b = v$, $p_c^b = v - h_c$.

(v) If $c_d > \mathcal{C}_2^b(\cdot)$, then $p_d^b = v$, $p_c^b = v - h_c - k$.

When the cost of disposable packaging is low ($c_d \leq \mathcal{C}_1^b$), the firm adopts a low-price strategy ($p_d^b = v - \xi$) to capture the entire market. In this region, charging a uniform price (i.e., $p_d^b = p_c^b$) is optimal, except when the disposable packaging cost is not sufficiently low and the hassle of using personal reusable packaging is relatively large (i.e., $c_d > h_c - \xi$ and $h_c > \xi$; see Lemma 2(ii)). In this case, the firm offers a small discount of $p_d^b - p_c^b = h_c - \xi$ to induce type-CI consumers to use personal reusable packaging and avoid the associated disposable packaging cost.

As the disposable packaging cost increases ($c_d > \mathcal{C}_1^b$), the firm raises the price of disposable packaging to extract surplus from eco-unconscious consumers, while offering a lower price for reusable packaging to retain eco-conscious consumers. This creates effective price discrimination: eco-conscious consumers self-select into reusable packaging by bearing the hassle cost h_c, whereas eco-unconscious consumers pay a premium for disposable packaging. Whether the firm also attracts type-CD consumers depends on the packaging retrieval cost k. When k is sufficiently high ($k \geq \min(\alpha(1-\theta)(v - h_c), \xi)$), it is optimal to exclude type-CD consumers and offer only a modest discount ($p_d^b - p_c^b = h_c$). When $k < \min(\alpha(1-\theta)(v - h_c), \xi)$, the firm sets a lower price for reusable packaging to attract both type-CI and type-CD consumers.

Finally, when the cost of disposable packaging is high ($c_d > \mathcal{C}_2^b$), the risk of eco-unconscious consumers switching to reusable packaging is no longer a big concern. The firm then sets a low price for reusable packaging to attract all eco-conscious and type-UI consumers, while charging $p_d^b = v$ to extract surplus from type-UD consumers who continue to prefer disposable packaging.

Overall, Lemma 2 provides a complete characterization of the firm's optimal differentiated pricing strategy when consumers can choose between disposable packaging and their personal reusable packaging. Peng et al. (2025) study a similar setting in which consumers can choose between these two packaging options, but their analysis primarily focuses on firms' communication strategies by assuming a uniform price across packaging types. Although they extend their model to allow the firm to offer a price discount to consumers who use their own containers, their results are based solely on numerical analysis and do not yield analytical characterizations. In contrast, Lemma 2 analytically demonstrates how firms can implement differentiated pricing to achieve price discrimination and shape consumer behavior. Specifically, Lemma 2(v) implies that some eco-unconscious consumers can also be encouraged to adopt personal reusable packaging when the disposable packaging cost is high, such that the firm is willing to offer a large discount (i.e., $p_d^b - p_c^b = h_c + k$). This mechanism may give rise to a counterintuitive environmental outcome when the firm introduces its own reusable packaging, as discussed in the next section.

4 Model with Firm-Owned Reusable Packaging

In the benchmark model, reuse adoption is driven solely by consumers using their personal reusable packaging. In this section, we explore a scenario in which the firm provides firm-owned reusable packaging, allowing consumers to borrow it with a deposit f and return it after each use to receive their deposit back. The returned reusable packaging is cleaned by the firm and reused by the next customer. Therefore, firm-owned reusable packaging can be viewed as an example of product servicizing, which refers to any strategy "under which a manufacturer retains the product's ownership and offers its functionality to customers on a pay-per-use basis" (Sun et al., 2024). Following Sun et al. (2024), we use a single-period model and focus on the steady-state setting.

4.1 Model Description

4.1.1 Consumer Return Decision

From the consumer's perspective, there are two key differences between using consumer-owned reusable packaging and firm-owned reusable packaging.

First, eco-conscious consumers do not incur the disutility when they use their reusable container, as they do not create packaging waste for this consumption. In contrast, with firm-owned reusable packaging, these consumers do not incur the disutility only if they successfully return the packaging after use. If they fail to do so, they still experience disutility, as the packaging exits the reuse loop

and needs to be replaced with new packaging, generating waste as in the case of using disposable packaging. For ease of exposition, we assume that the disutility associated with packaging waste from unreturned reusable packaging is also equal to ξ, the same as that from disposable packaging. In practice, waste from disposable packaging and from unreturned reusable packaging may have different environmental impacts, which could lead eco-conscious consumers to experience different levels of disutility. Our model can be extended to incorporate such heterogeneous environmental disutility (see Online Appendix II). The main results remain robust under this extension.

Second, the timing and source of the hassle differ between the two models. For consumer-owned reusable packaging, the hassle (such as cleaning the packaging) is incurred *before* the purchase, as consumers must prepare their packaging in advance. In contrast, the primary hassle associated with firm-owned reusable packaging stems from the need to return the packaging *after* the purchase. This creates uncertainty for consumers at the time of purchase, as they cannot know for sure how the return process will fit into their uncertain schedules. The challenge of returning firm-owned reusable packaging closely parallels the consumer rebate redemption problem: in both cases, consumers must incur a post-purchase hassle, such as returning packaging to receive a deposit refund or mailing forms to redeem a rebate. In addition, it is not uncommon for consumers to fail to return firm-owned reusable packaging or to redeem the rebate. This analogy motivates our use of a similar modeling approach to capture consumer behavior. Specifically, following the framework of Lu and Moorthy (2007), consumers may face one of two possible return scenarios after consuming the product: an effortless-return state or an effortful-return state. An effortless-return state (resp. effortful-return state) is characterized by a low (resp. high) perceived hassle cost of returning the packaging, holding the physical return process fixed. This state is realized only after purchase, when the consumer needs to return the packaging; for example, the consumer may unexpectedly have a flexible schedule (i.e., effortless-return state), or instead face an unexpectedly busy schedule or time constraints that make returning the packaging inconvenient (i.e., effortful-return state). Let $\beta \in (0,1)$ denote the probability that a consumer is in the effortless-return state. The return hassle cost is given by Φh_f, where $\Phi = 1$ in the effortless-return state (with probability β) and $\Phi = \phi > 1$ in the effortful-return state (with probability $1-\beta$). Here, h_f captures the baseline time and travel effort required to return the packaging to a return point. This baseline hassle can be affected by operational factors such as the density of return points; for example, a denser return network can reduce the walking distance or travel time needed to complete the return, thereby lowering h_f. The parameter ϕ captures the increase in perceived hassle when consumers face an unexpectedly busy schedule or time constraints,

i.e., in the effortful-return state.

Therefore, consumers must make both a packaging choice at the point of purchase and if they choose firm-owned reusable packaging, a return decision after consumption. We first examine the return decision. If a consumer returns the packaging on time, they receive the deposit f but incur a hassle cost of Φh_f, yielding a net payoff of $f - \Phi h_f$. However, if the consumer fails to return the packaging (thereby generating packaging waste), eco-conscious consumers incur a disutility of ξ (i.e., a net payoff of $-\xi$) while eco-unconscious consumers incur no such disutility (i.e., a net payoff of 0) as they do not care about the environmental implications. Consumers compare these net payoffs when making their return decisions, which depend on both their environmental preference and their realized return state Φ. Specifically, eco-conscious consumers return the packaging if and only if $f \geq \Phi h_f - \xi$, while eco-unconscious consumers return the packaging if and only if $f \geq \Phi h_f$. As a result, given the probability distribution of Φ, the probability of returning the packaging is given by Equation (9) for eco-conscious consumers (ρ_c) and eco-unconscious consumers (ρ_u).

$$\rho_c = \begin{cases} 0, & \text{if } f < h_f - \xi, \\ \beta, & \text{if } h_f - \xi \leq f < \phi h_f - \xi, \\ 1, & \text{if } f \geq \phi h_f - \xi, \end{cases} \qquad \rho_u = \begin{cases} 0, & \text{if } f < h_f, \\ \beta, & \text{if } h_f \leq f < \phi h_f, \\ 1, & \text{if } f \geq \phi h_f. \end{cases} \tag{9}$$

These expressions reflect that consumers return the packaging only when the deposit f is sufficiently large relative to the perceived return hassle. When the deposit is low, no consumers return the packaging regardless of their return state. For intermediate deposit levels, only consumers in the effortless-return state return the packaging, yielding a return probability of β. When the deposit is sufficiently high, consumers return the packaging in both return states, resulting in a return probability of one. Throughout the paper, we assume that $\phi > 1 + \frac{\xi}{h_f}$. This condition ensures that a higher incentive (e.g., a deposit) is required to motivate packaging returns in the effortful-return state compared to the effortless-return state. This assumption holds regardless of environmental preference (implying $\phi h_f - \xi > h_f$) and reflects the realistic possibility that the additional inconvenience outweighs the consumer's environmental motivation.

Our model captures three key facts: (i) consumers may fail to return the packaging, especially when they are in the effortful-return state and the deposit is not sufficiently large, (ii) a higher deposit f can encourage more return, and (iii) eco-conscious consumers are more likely to return firm-owned reusable packaging than eco-unconscious consumers, because they have intrinsic motivation to avoid the disutility ξ of creating packaging waste. Note that the firm will always set $f \geq h_f - \xi$; otherwise,

no consumers would return the firm-owned reusable packaging, effectively turning it into a more expensive form of disposable packaging for the firm. (A more detailed discussion of the firm's cost structure is provided later.)

4.1.2 Consumer Demand

We next move one step backward to consider the purchase decision with packaging choice. At this stage, the return hassle has not yet been realized. Consumers therefore make their decisions based on the expected payoff from the potential outcomes at the return stage. Specifically, the expected payoff from the return decision is

$$\mathbb{E}_\Phi[\max(f - \Phi h_f, -\Xi_j)] = \beta \max(f - h_f, -\Xi_j) + (1-\beta)\max(f - \phi h_f, -\Xi_j),$$

where β denotes the probability that consumers are in the effortless-return state, $1-\beta$ denotes the probability that they are in the effortful-return state, and $\Xi_j = 0$ for $j \in \{UI, UD\}$ and $\Xi_j = \xi$ for $j \in \{CI, CD\}$.

Let $p_f \leq p_d$ denote the product price for firm-owned reusable packaging. If consumers purchase the product with firm-owned reusable packaging, they need to pay the deposit f in addition to the product price p_f, and their utility is:

$$\begin{aligned} u_{F,j} &= v - p_f - f + \mathbb{E}_\Phi[\max(f - \Phi h_f, -\Xi_j)] \\ &= v - p_f - \mathbb{E}_\Phi[\min(\Phi h_f, f + \Xi_j)]. \end{aligned} \tag{10}$$

If consumers instead choose disposable packaging or consumer-owned reusable packaging, their utilities remain $u_{D,j}$ and $u_{C,j}$ as defined in the benchmark model (i.e., Equation (1)). Comparing $u_{F,j}$ with $u_{D,j}$, eco-conscious consumers prefer firm-owned reusable packaging to disposable packaging when $p_d - p_f \geq \mathbb{E}_\Phi[\min(\Phi h_f, f+\xi)] - \xi$, while eco-unconscious consumers require a larger discount, with $p_d - p_f \geq \mathbb{E}_\Phi[\min(\Phi h_f, f)]$. In other words, eco-conscious consumers are more likely than eco-unconscious consumers to adopt the firm-owned reusable packaging. Given the three available packaging options, type-j consumers choose the option that yields the highest non-negative utility among $u_{D,j}$, $u_{C,j}$, and $u_{F,j}$. Because consumers in the same segment make the same utility comparison across packaging options, their choices can be characterized at the segment level. As in the benchmark model, $d_{D,j}$ and $d_{C,j}$ denote the segment-level demands for disposable packaging and consumer-owned reusable packaging, respectively. In addition, let $d_{F,j}$ denote the segment-level demand for firm-owned reusable packaging. In the expressions below, each demand term equals M_j (the size of segment j) when the stated conditions hold and equals zero otherwise, where the first condition ensures non-negative

purchase utility, and the remaining conditions identify the utility-maximizing packaging option.

- For $j \in \{CI, CD\}$,

$$d_{D,j} = M_j \quad \text{if } p_d \le v - \xi \text{ and}$$
$$p_d < p_c + h_c + K_j - \xi \text{ and } p_d < p_f + \mathbb{E}_\Phi[\min(\Phi h_f, f + \xi)] - \xi, \tag{11}$$
$$d_{C,j} = M_j \quad \text{if } p_c \le v - h_c - K_j \text{ and}$$
$$p_c \le p_d + \xi - h_c - K_j \text{ and } p_c \le p_f + \mathbb{E}_\Phi[\min(\Phi h_f, f + \xi)] - h_c - K_j, \tag{12}$$
$$d_{F,j} = M_j \quad \text{if } p_f \le v - \mathbb{E}_\Phi[\min(\Phi h_f, f + \xi)] \text{ and}$$
$$p_f \le p_d + \xi - \mathbb{E}_\Phi[\min(\Phi h_f, f + \xi)] \text{ and } p_f < p_c + h_c + K_j - \mathbb{E}_\Phi[\min(\Phi h_f, f + \xi)]. \tag{13}$$

- For $j \in \{UI, UD\}$,

$$d_{D,j} = M_j \quad \text{if } p_d \le v \text{ and}$$
$$p_d \le p_c + h_c + K_j \text{ and } p_d \le p_f + \mathbb{E}_\Phi[\min(\Phi h_f, f)], \tag{14}$$
$$d_{C,j} = M_j \quad \text{if } p_c \le v - h_c - K_j \text{ and}$$
$$p_c < p_d - h_c - K_j \text{ and } p_c \le p_f + \mathbb{E}_\Phi[\min(\Phi h_f, f)] - h_c - K_j, \tag{15}$$
$$d_{F,j} = M_j \quad \text{if } p_f \le v - \mathbb{E}_\Phi[\min(\Phi h_f, f)] \text{ and}$$
$$p_f < p_d - \mathbb{E}_\Phi[\min(\Phi h_f, f)] \text{ and } p_f < p_c + h_c + K_j - \mathbb{E}_\Phi[\min(\Phi h_f, f)]. \tag{16}$$

Using the segment-level demands defined above, the total numbers of consumers who use disposable packaging (d_D) and consumer-owned reusable packaging (d_C) are obtained from Equations (6) and (7), respectively. In addition, the total number of consumers who use firm-owned reusable packaging is given by

$$d_F = \sum_{j \in \{CI, CD, UI, UD\}} d_{F,j}. \tag{17}$$

Among those consumers who borrow and use the firm-owned reusable packaging, some may eventually return it while others may not, with the return probabilities ρ_c and ρ_u given in Equation (9). We use $d_{F,r}$ to denote the number of consumers who return the firm-owned reusable packaging, and $d_{F,u}$ to denote the number of consumers who do not return it. Therefore, we have

$$d_{F,r} = \sum_{j \in \{CI, CD\}} d_{F,j}\rho_c + \sum_{j \in \{UI, UD\}} d_{F,j}\rho_u, \tag{18}$$

$$d_{F,u} = \sum_{j \in \{CI,CD\}} d_{F,j}(1-\rho_c) + \sum_{j \in \{UI,UD\}} d_{F,j}(1-\rho_u). \tag{19}$$

4.1.3 Firm Profit

Let $\rho \in [0,1]$ represent the overall return rate, defined as the percentage of firm-owned reusable packaging that is returned to the firm. Then, we have

$$\rho(f) = \frac{d_{F,r}(f)}{d_F(f)}. \tag{20}$$

Unlike disposable packaging, firm-owned reusable packaging can be reused multiple times. Let $T > 1$ denote the maximum number of use cycles the firm-owned packaging can sustain. Since some consumers may not return the packaging after borrowing it, the packaging may not reach its full potential lifespan. Therefore, it is necessary to calculate the *expected average* cost per use for firm-owned reusable packaging. We first derive the *expected number of use cycles* for firm-owned reusable packaging, denoted as τ. Given the return rate ρ, the number of use cycles follows a Geometric distribution with a capped number of trials T, and thus we have

$$\tau(\rho) = 1 + \rho + \cdots + \rho^{T-1}. \tag{21}$$

Note that $\tau(\rho)$ is increasing in ρ, with $\tau(1) = T$.

The cost associated with firm-owned reusable packaging consists of two components. First, the firm incurs a procurement cost $c_{r,m}$ for each unit when it is put into use for the first time. Second, for each reusable packaging item that is returned by consumers, the firm must pay an additional cost $c_{r,o} > 0$ for collection and cleaning to ensure it is suitable for the next use. We assume $c_{r,o} < c_{r,m}$; otherwise, it would be more economical for the firm to purchase new packaging each time, and the "reusable packaging" becomes "disposable packaging". Therefore, given the expected number of use cycles $\tau(\rho)$, the *average* cost per use of the firm-owned reusable packaging is:

$$c_r(\rho) = \frac{c_{r,m} + (\tau(\rho) - 1)c_{r,o}}{\tau(\rho)}. \tag{22}$$

We can see that $c_r(\rho)$ decreases as ρ increases, since a higher return rate ρ leads to a greater expected number of use cycles, thereby spreading the procurement cost $c_{r,m}$ over more uses. We assume that $c_r(1) > c_d$ such that the average cost of firm-owned reusable packaging is still higher than disposable packaging, even if it is fully utilized. Such an assumption can capture the current practice, due to the high operational cost $c_{r,o}$ (Circular Economy Portugal, 2021; McKinsey, 2022). Therefore, in our model, the only motivation for the firm to offer its reusable packaging is to meet the demands of

eco-conscious consumers, which is aligned with the current practice (McKinsey, 2022; Fofana, 2024).[6]

Given the demand functions, the firm sets the product price p_d (with disposable packaging), p_c (with consumer-owned reusable packaging), and p_f along with a deposit f (with firm-owned reusable packaging), in order to maximize its profit function:

$$\begin{aligned}\pi(p_d, p_c, p_f, f) = \quad & (p_d - c_d)d_D + p_c d_C \\ & + \left[(p_f + f)d_{F,u} + p_f d_{F,r} - (d_{F,u} + d_{F,r})c_r(\rho(f))\right].\end{aligned} \tag{23}$$

The first line captures the total profit from demand associated with disposable and consumer-owned reusable packaging, while the second line reflects profit from demand associated with firm-owned reusable packaging. Note that when consumers choose not to return the firm-owned reusable packaging, the deposit f becomes the firm's revenue.

4.2 Equilibrium Analysis

We use superscript $(\cdot)^f$ to denote the equilibrium outcome in the presence of firm-owned reusable packaging.

Proposition 1.

(i) The firm will offer firm-owned reusable packaging (i.e., $\pi^f > \pi^b$) if and only if $c_{r,o} < \mathcal{C}^f(c_d, v, \alpha, \theta, \beta, \phi, h_c, h_f, \xi, k, c_{r,m}, T)$ for some threshold function $\mathcal{C}^f(\cdot)$.

(ii) When the cost of disposable packaging is small, there are instances in which the firm offers firm-owned reusable packaging for a small fraction of eco-conscious consumers, but not for a large fraction. (Formally, if $c_d < \mathcal{C}_1^b(\cdot)$, where $\mathcal{C}_1^b$ is defined in Lemma 2, then there exist $\alpha_1 < \alpha_2$ such that $c_{r,o} < \mathcal{C}^f\big|_{\alpha=\alpha_1}$ and $c_{r,o} > \mathcal{C}^f\big|_{\alpha=\alpha_2}$.) Under this condition, $p_d^f|_{\alpha=\alpha_1} > p_d^b|_{\alpha=\alpha_1}$, and the changes of consumer purchase decisions are summarized in Table 2.

Proposition 1(i) shows that it can be profitable for the firm to offer firm-owned reusable packaging when the operational cost is not large (i.e., $c_{r,o} < \mathcal{C}^f$). Introducing firm-owned reusable packaging generates two effects. First, it attracts eco-conscious consumers by offering more reuse options. In fact, firm-owned reusable packaging is especially appealing to type-CD consumers, who care about packaging waste but lack immediate access to personal reusable containers at the point of purchase. Second, because eco-conscious consumers are more likely than eco-unconscious consumers to adopt

[6] If $c_r(1) \leq c_d$, firm-owned reusable packaging may also create a cost-saving motive by replacing disposable packaging. However, attracting eco-unconscious consumers to adopt firm-owned reusable packaging requires a price incentive satisfying $p_d - p_f \geq h_f$. Thus, this cost-saving motive is relevant only when $c_r(1) < c_d - h_f$. As long as $c_r(1) \geq c_d - h_f$, the firm has no motivation to induce eco-unconscious consumers to use firm-owned reusable packaging, and its motivation for introducing the program remains serving eco-conscious consumers. Under this weaker condition, our main findings continue to hold.

Table 2: Changes in Consumer Purchase Decisions under Proposition 1(ii)

	type-CI	type-CD	type-UI	type-UD
Small size of eco-conscious segment ($\alpha = \alpha_1$)	$CRP/FRP_r/FRP_u$	FRP_r/FRP_u	DP	DP
Large size of eco-conscious segment ($\alpha = \alpha_2$)	CRP/DP	DP	DP	DP

CRP = purchasing with consumer-owned reusable packaging.
DP = purchasing with disposable packaging.
FRP_r = purchasing the product with firm-owned reusable packaging with successful return at all states.
FRP_u = purchasing the product with firm-owned reusable packaging with unsuccessful return at effortful-return state.

the firm-owned reusable packaging, this option serves as an effective screening device that enables the firm to implement more precise price discrimination. Together with the consumer-owned option, offering firm-owned reusable packaging gives the firm greater flexibility in pricing and can further enhance profitability, as long as its operational cost $c_{r,o}$ is not too high.

Proposition 1(ii) further examines the impact of the size of the eco-conscious consumer segment (α) on the firm's reusable packaging decisions. Somewhat surprisingly, a higher fraction of eco-conscious consumers can weaken the firm's incentive to introduce firm-owned reusable packaging when the cost of disposable packaging is low (i.e., $c_d < \mathcal{C}_1^b$). The intuition is as follows. As shown in Lemma 2, when the disposable packaging cost is low, the firm optimally sets a low price to serve the entire market. Under this condition, the market-expansion effect of introducing firm-owned reusable packaging is limited. Instead, the primary role of firm-owned reusable packaging is to facilitate price discrimination, allowing the firm to charge a higher product price p_d and extract additional surplus from eco-unconscious consumers who continue to use disposable packaging (i.e., $p_d^f|_{\alpha=\alpha_1} > p_d^b|_{\alpha=\alpha_1}$). However, as the market becomes more eco-conscious (i.e., as α increases), the mass of eco-unconscious consumers shrinks, weakening the effectiveness of this price-discrimination mechanism. Consequently, an increase in the share of eco-conscious consumers reduces the profitability of introducing firm-owned reusable packaging, thereby discouraging the firm from offering such a program (i.e., $\mathcal{C}^f|_{\alpha=\alpha_1} > \mathcal{C}^f|_{\alpha=\alpha_2}$). As shown in Table 2, eco-conscious consumers switch to either their personal reusable packaging or the disposable option as a result.

This result highlights that a more eco-conscious market does not always make a firm-owned program more attractive, especially when the disposable packaging is inexpensive. Although a more eco-conscious customer base implies stronger demand for reuse, it also reduces the price-discrimination benefit of the firm-owned option. Therefore, when deciding whether to introduce firm-owned reusable packaging, profit-driven firms should assess whether it creates sufficient incremental value relative to the existing consumer-owned option, rather than assuming that a larger eco-conscious market automatically strengthens the case for firm-owned reuse.

In the following discussion, we focus on the case when $c_{r,o} < \mathcal{C}^f$ such that the firm is willing to offer its reusable packaging. When consumers adopt reusable packaging, either consumer-owned or firm-owned, they incur certain hassle costs. Therefore, the firm needs to reduce the product price as compensation. Lemma 3 characterizes the optimal pricing strategy based on the hassle costs of two types of reusable packaging. The four strategies identified in the lemma are depicted in Figure 1.

Lemma 3. *There exist threshold functions* $\mathcal{H}_c(\alpha, \theta, \beta, \phi, \xi, c_{r,o}, c_{r,m}, T, h_f)$, $\mathcal{H}_{f1}(\alpha, \theta, \beta, \phi, \xi, c_{r,o}, c_{r,m}, T)$ *and* $\mathcal{H}_{f2}(\alpha, \theta, \beta, \phi, \xi, c_{r,o}, c_{r,m}, T)$ *such that the firm's optimal pricing strategy is as follows:*

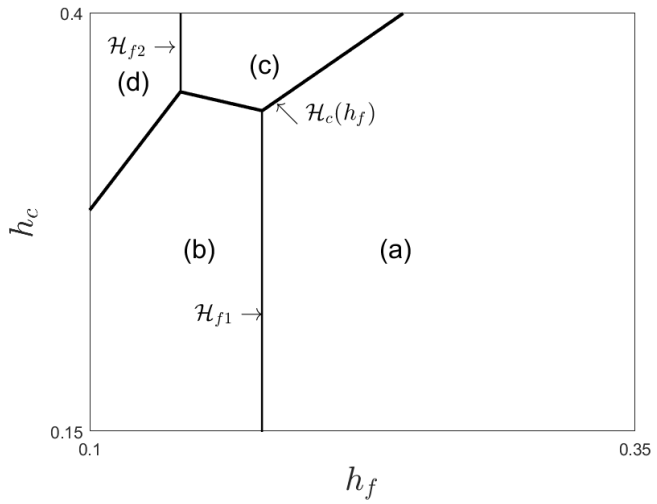
(a) If $h_c < \mathcal{H}_c(\cdot)$ *and* $h_f \geq \mathcal{H}_{f1}(\cdot)$, *then* $p_d^f = v - (1-\beta)\xi$, $p_c^f = \min(v - (1-\beta)\xi, v - h_c)$, $p_f^f = v - h_f - (1-\beta)\xi$, *and* $f^f = h_f$.

(b) If $h_c < \mathcal{H}_c(\cdot)$ *and* $h_f < \mathcal{H}_{f1}(\cdot)$, *then* $p_d^f = v$, $p_c^f = v - h_c$, $p_f^f = v - (\beta + (1-\beta)\phi)h_f$, *and* $f^f = \phi h_f$.

(c) If $h_c \geq \mathcal{H}_c(\cdot)$ *and* $h_f \geq \mathcal{H}_{f2}(\cdot)$, *then* $p_d^f = v - (1-\beta)\xi$, $p_c^f = v - (1-\beta)\xi$, $p_f^f = v - h_f - (1-\beta)\xi$, *and* $f^f = h_f$.

(d) If $h_c \geq \mathcal{H}_c(\cdot)$ *and* $h_f < \mathcal{H}_{f2}(\cdot)$, *then* $p_d^f = v$, $p_c^f = v$, $p_f^f = v - (\beta + (1-\beta)\phi)h_f$, *and* $f^f = \phi h_f$.

Figure 1: Optimal Strategy with Firm-Owned Reusable Packaging (Based on Lemma 3)



In this example: $v = 0.9$, $k = 0.3$, $\xi = 0.3$, $c_d = 0.1$, $\phi = 8$, $\alpha = 0.4$, $\theta = 0.4$, $\beta = 0.9$, $c_{r,m} = 0.6$, $c_{r,o} = 0.1$, $T = 40$.

When the firm introduces its own reusable packaging to attract type-CD consumers, this option may also appeal to type-CI consumers. However, if type-CI consumers switch from using their personal reusable packaging to the firm's reusable packaging, the firm incurs a higher total packaging cost. Therefore, when consumers find it convenient to use their personal reusable packaging (i.e., $h_c < \mathcal{H}_c$), as shown in Lemma 3(a) and (b), the firm is willing to offer a price incentive ($p_d^f - p_c^f > 0$) to

encourage type-CI consumers to continue doing so. Conversely, when personal reusable packaging remains inconvenient (i.e., $h_c \geq \mathcal{H}_c$), as shown in Lemma 3(c) and (d), the firm discontinues the price incentive ($p_d^f = p_c^f$) to encourage type-CI consumers to adopt the firm-owned reusable packaging instead, thereby minimizing the incentive cost.

Regarding the choice of deposit f^f, the firm faces a trade-off between encouraging returns and promoting the adoption of firm-owned reusable packaging. On one hand, a higher deposit f can incentivize more consumers to return the packaging, thereby reducing the packaging cost c_r. On the other hand, a higher deposit may discourage consumers from adopting the firm's reusable packaging in the first place. Intuitively, when the hassle cost of returning the packaging h_f is high (respectively, low), consumers already have a low (respectively, high) willingness to adopt the firm's reusable packaging. Therefore, as shown in Lemma 3(a) and (c) (respectively, (b) and (d)), the firm should set a correspondingly low (respectively, high) deposit f^f. Based on the demand model, in cases (a) and (c) of Lemma 3, we can find that the return rate is $\rho = \beta$, i.e., consumers return the firm-owned reusable packaging only when they are in the effortless-return state; in cases (b) and (d), we have $\rho = 1$, i.e., consumers always return the packaging.

4.3 Impact of Firm-Owned Reusable Packaging

Let us examine the environmental implications of offering firm-owned reusable packaging that arise from changes in the firm's pricing decisions and consumers' shopping behaviors. Specifically, we focus on the waste created from disposing packaging and introduce the following metric:

$$W \triangleq \text{average packaging waste per unit of product sold.}$$

The metric reflects the success of the transition to a circular business model. A smaller W indicates that less packaging is waste generated, which benefits the environment. In the benchmark model without firm-owned reusable packaging, we have $W^b = \frac{d_D^b}{d_D^b + d_C^b}$; that is, the packaging waste is generated from the use of disposable packaging. Every order fulfilled with disposable packaging requires the production of a new disposable container, which becomes waste after use. Furthermore, when firm-owned reusable packaging is available, it can also generate waste if reusable containers exit the reuse loop due to consumers' failure to return them, thereby requiring the firm to replace the packaging and increasing total waste. Therefore, we have $W^f = \frac{d_D^f + d_{F,u}^f}{d_D^f + d_F^f + d_C^f}$. (In practice, waste generated from the use of disposable packaging and from the failure to return reusable packaging may entail different environmental impacts. In Online Appendix II, we modify the environmental metric to explicitly capture the heterogeneous environmental implications of these two behaviors. Our main

results remain valid.)

Proposition 2. *Compared to the benchmark model, when the firm chooses to offer its reusable packaging, $W^f > W^b$ if $c_d > \mathcal{C}_2^b(\cdot)$, where $\mathcal{C}_2^b(\cdot)$ is defined in Lemma 2. Under this condition, $p_d^f \leq p_d^b$, $p_c^f > p_c^b$, and the changes of consumer purchase decisions are summarized in Table 3.*

Table 3: Changes in Consumer Purchase Decisions under Proposition 2

	type-CI	type-CD	type-UI	type-UD
Without firm-owned reusable packaging	CRP	CRP	CRP	DP
With firm-owned reusable packaging	$CRP/FRP_r/FRP_u$	FRP_r/FRP_u	DP	DP

CRP = purchasing with consumer-owned reusable packaging.
DP = purchasing with disposable packaging.
FRP_r = purchasing the product with firm-owned reusable packaging with successful return at all states.
FRP_u = purchasing the product with firm-owned reusable packaging with unsuccessful return at effortful-return state.

Proposition 2 reveals a counterintuitive effect of offering firm-owned reusable packaging: although consumers are given more reusable options, the average packaging waste per unit of product may actually increase (i.e., $W^f > W^b$). This negative environmental outcome is largely driven by changes in the packaging choices of *eco-unconscious* consumers, as shown in Table 3. As explained in the discussion of Lemma 2, when the disposable packaging cost is high (i.e., $c_d > \mathcal{C}_2^b$), the firm is willing to offer a large discount, $p_d^b - p_c^b$, to achieve price discrimination. However, this generous discount also unintentionally incentivizes some eco-unconscious (i.e., type-UI) consumers to adopt personal reusable packaging. From the for-profit firm's perspective, these type-UI consumers can be viewed as free riders who benefit from price discounts targeted at eco-conscious consumers, thereby reducing the firm's profit. With firm-owned reusable packaging, the firm gains an additional lever, beyond pricing, to better segment the market. In particular, the firm can reduce the price discount $p_d^f - p_c^f$ for consumer-owned reusable packaging by lowering p_d and increasing p_c, as shown in Proposition 2. This adjustment pushes type-UI consumers toward disposable packaging while ensuring that eco-conscious consumers continue to use reusable options, either consumer-owned or firm-owned. As a result, although the firm's profit is enhanced through more precise price discrimination, the shift in type-UI consumers' packaging choices from reusable to disposable packaging leads to a deterioration in the environmental metric.

A key condition for the backfire effect identified in Proposition 2 is that the disposable packaging cost is high. In practice, a high c_d can arise when government policies increase the cost of using disposable packaging, such as plastic taxes or extended producer responsibility requirements for packaging (Cartwright, 2025). Under such policies, firms may have stronger incentives to reduce their reliance

on disposable packaging and offer larger discounts for consumer-owned reusable packaging. Proposition 2 shows that introducing firm-owned reusable packaging in such settings can unintentionally weaken these incentives and increase packaging waste.

Proposition 2 highlights an important concern: while offering firm-owned reusable packaging makes the reuse option accessible to all consumers, it does not necessarily lead to reduced packaging waste. A successful transition to reuse requires the engagement of both eco-conscious and eco-unconscious consumers. Unlike eco-conscious consumers, eco-unconscious consumers will only adopt reusable packaging when the price incentive is substantial. However, for-profit firms have little motivation to offer sufficient price discounts to encourage eco-unconscious consumers to adopt firm-owned reusable packaging. Given the potential substitution effect between firm-owned reusable packaging and price discounts for personal reusable packaging, a profit-driven company may prioritize cost considerations over environmental goals, potentially leading to undesirable outcomes.

5 Convenience of Reusable Packaging

The inconvenience associated with reusable packaging is a primary barrier to its adoption. Therefore, in addition to offering price incentives as compensation, it is crucial to directly enhance the convenience of using reusable packaging. In our model, convenience improvements are represented by reductions in the hassle cost, h_c (for personal reusable packaging) and h_f (for firm-owned reusable packaging). In this section, we conduct a sensitivity analysis to evaluate the impact of convenience improvements on the firm's profit and reuse adoption. It is important to note that, in practice, enhancing convenience typically entails additional costs for the firm. However, this analysis isolates these costs to focus on the other key mechanisms.

When consumers use personal reusable packaging, they must carry it while shopping and clean it before purchasing the product, creating inconvenience. Then, it could be more convenient for consumers to use personal reusable packaging if they do not need to clean it by themselves. For example, Starbucks Korea announced plans to install tumbler washing machines in all its stores by 2026, making it even easier for customers to adopt sustainable practices (Yonhap, 2024). The availability of mug washers can significantly lower the hassle for consumers using personal reusable cups (i.e., reducing h_c in our model), as they no longer need to handle the cleaning themselves.

When consumers use firm-owned reusable packaging, the primary inconvenience is the need to return it after use. Increasing the number or density of return points can reduce the baseline time and travel effort required to complete the return process (i.e., reducing h_f in our model). For instance,

during the trial of its "Borrow a Cup" program on the Arizona State University campus, Starbucks allowed customers to return their borrowed cups to designated return bins around campus, in addition to returning them at Starbucks stores (Starbucks, 2023). Such initiatives aim to make returning firm-owned reusable packaging more convenient (i.e., reducing h_f in our model) for consumers.

We first look at the convenience improvement of reusable packaging on the firm's profit.

Proposition 3. *When the firm offers its reusable packaging,*

(i) A decrease in the hassle of consumer-owned reusable packaging always increases the profit. (Formally, π^f is decreasing in h_c.)

(ii) A decrease in the hassle of firm-owned reusable packaging always increases the profit. (Formally, π^f is decreasing in h_f.)

Proposition 3 shows that improving the convenience of reusable packaging has a positive impact on the firm's profit, regardless of the type of reusable packaging. This is because the convenience improvement of reusable packaging can help the firm save on the incentive cost by increasing the price for consumer-owned reusable packaging (i.e., p_c) and firm-owned reusable packaging (i.e., p_f). While the profit implications are intuitive, the next proposition reveals some surprising results regarding the environmental impact of improving the convenience of reusable packaging.

Proposition 4. *When the firm offers its reusable packaging,*

(i) A decrease in the hassle of consumer-owned reusable packaging always reduces the average packaging waste per unit of product sold. (Formally, W^f is weakly increasing in h_c.)

(ii) There are instances where the average packaging waste per unit of product sold increases as the hassle of using firm-owned reusable packaging decreases, particularly when using consumer-owned reusable packaging is not very convenient. (Formally, there exist h_{f1}, h_{f2} such that $\mathcal{H}_{f2}(\cdot) < h_{f1} < h_{f2}$ and $W^f|_{h_f=h_{f1}} > W^f|_{h_f=h_{f2}}$ if $h_c > \mathcal{H}^*(\cdot)$ for some threshold function $\mathcal{H}^*(\alpha, \theta, \beta, \phi, \xi, c_{r,o}, c_{r,m}, T)$, where $\mathcal{H}_{f2}(\cdot)$ is defined in Lemma 3). Under this condition, $p_c^f|_{h_f=h_{f1}} > p_c^f|_{h_f=h_{f2}}$, $p_f^f|_{h_f=h_{f1}} > p_f^f|_{h_f=h_{f2}}$, and the changes of consumer purchase decisions are summarized in Table 4.

Conventional wisdom suggests that improving the convenience of using reusables should promote their adoption (Hubbub, 2022). While this holds true for consumer-owned reusable packaging, as demonstrated in Proposition 4(i), Proposition 4(ii) reveals that the same may not apply to firm-owned reusable packaging, particularly when the hassle associated with consumer-owned reusable packaging remains high (i.e., $h_c > \mathcal{H}^*$).

Table 4: Changes in Consumer Purchase Decisions under Proposition 4(ii)

	type-CI	type-CD	type-UI	type-UD
High hassle of firm-owned reusable packaging ($h_f = h_{f2}$)	CRP	FRP_u	DP	DP
Low hassle of firm-owned reusable packaging ($h_f = h_{f1}$)	FRP_u	FRP_u	DP	DP

CRP = purchasing with consumer-owned reusable packaging.
DP = purchasing with disposable packaging.
FRP_r = purchasing the product with firm-owned reusable packaging with successful return at all states.
FRP_u = purchasing the product with firm-owned reusable packaging with unsuccessful return at effortful-return state.

This counterintuitive environmental outcome is driven by a shift in the packaging choices of type-CI consumers, as shown in Table 4. When the hassle of using firm-owned reusable packaging is high (i.e., $h_f = h_{f2}$), type-CI consumers use their personal reusable containers. As firm-owned reusable packaging becomes more convenient (i.e., h_f decreases from h_{f2} to h_{f1}), it becomes more attractive to type-CI consumers. At this point, retaining these consumers with personal reusable packaging would require prohibitively large discounts, especially when $h_c > \mathcal{H}^*$. To avoid high incentive costs, the firm, as described in Lemma 3(c), chooses to discontinue offering discounts for personal reusable packaging (i.e., $p_c^f = p_d^f$), prompting type-CI consumers to switch to firm-owned reusable packaging. In this case, since the hassle of packaging return is not small enough (i.e., $h_{f1} > \mathcal{H}_{f2}$), according to Lemma 3(c), the firm sets a small deposit so that consumers return the firm-owned reusable packaging only when they are in the effortless-return state. Because of this non-return behavior, some firm-owned reusable packaging fails to reenter the reuse loop, thereby increasing the average packaging waste per unit of product sold.

Based on the analysis in Proposition 3 and Proposition 4, we draw the following conclusions. It is beneficial for the firm to focus on improving the convenience of consumer-owned reusable packaging, such as reducing the cleaning hassle by installing washing stations in stores, as this can lead to a win-win outcome by increasing the firm's profit while reducing packaging waste. In contrast, although improving the return convenience of firm-owned reusable packaging (e.g., making return points more accessible) can also increase profit, it may displace consumer-owned reuse and lead to a worse environmental outcome, because firm-owned reusable packaging is subject to non-return risk that can increase average packaging waste per unit of product sold.

6 Calibrated Numerical Studies

In this section, we conduct numerical studies to illustrate the environmental implications of firm-owned reusable packaging programs. Specifically, we first quantify the overall impact of introducing firm-owned reusable packaging on packaging waste and evaluate how often the waste-increasing out-

come in Proposition 2 occurs under calibrated parameter values. Then, we examine the environmental impact of improving the convenience of firm-owned reusable packaging and evaluate how often the backfiring effect in Proposition 4(ii) arises.

To conduct these analyses, we randomly generate scenarios based on the following parameter distributions. The range of each parameter is calibrated using multiple sources of external evidence, including industry and consulting reports, consumer surveys, and related academic research, to reflect empirically plausible market conditions and consumer behavior in real-world reusable packaging systems, with details provided in Online Appendix III: $T \sim U(20, 40)$, $\beta \sim U(0.5, 0.9)$, $c_d \sim U(0.05, 0.15)$, $c_{r,m} \sim U(0.3, 0.7)$, $c_{r,o} \sim U(0.1, 0.2)$, $v \sim U(0.8, 1.2)$, $\alpha \sim U(0.2, 0.6)$, $\theta \sim U(0.4, 0.6)$, $h_c \sim U(0.15, 0.4)$, $\xi \sim U(0.15, 0.4)$, $h_f \sim U(0.1, 0.35)$, $k \sim U(0.15, 0.4)$, and $\phi \sim U(7, 13)$. To ensure consistency with the analysis in the main model, we impose the same set of conditions: $h_c > c_d$ and $c_r(1) > c_d$, and thereby exclude scenarios that do not satisfy these assumptions. Furthermore, since the primary focus of this paper is the role of firm-owned reusable packaging, we exclude scenarios in which it is not profitable for the firm to introduce such packaging. Finally, we generate 100,000 scenarios. In each scenario, we determine the firm's optimal decisions without and with firm-owned reusable packaging, i.e., (p_d^b, p_c^b) and $(p_d^f, p_c^f, p_f^f, f^f)$, respectively.

First, we quantify the impact of introducing firm-owned reusable packaging on packaging waste. Across the calibrated scenarios, the relative reduction in packaging waste, defined as $\frac{W^b - W^f}{W^b}$, is 10.4% on average. The median reduction is approximately 14.5%, with the interquartile range spanning from 10.5% to 22.4%. These statistics indicate that firm-owned reusable packaging substantially reduces packaging waste in most simulated scenarios. Nevertheless, waste reduction is not guaranteed: introducing firm-owned reusable packaging increases average packaging waste per unit of product sold in some scenarios (i.e., $W^f > W^b$).

Next, we evaluate the likelihood of such adverse environmental outcomes (i.e., $W^f > W^b$). Recall that in Proposition 2, we identify c_d as a conditioning variable, with the result holding when c_d is sufficiently large. To assess the empirical relevance of this condition, we compute the proportion of scenarios in which $W^f > W^b$ across four intervals of c_d: $[0.05, 0.075)$, $[0.075, 0.1)$, $[0.1, 0.125)$, and $[0.125, 0.15]$. The corresponding proportions are 5.3%, 6.0%, 7.3%, and 8.7%, respectively. Furthermore, consistent with Proposition 2, the likelihood of observing $W^f > W^b$ increases monotonically with c_d. Thus, although the introduction of firm-owned reusable packaging reduces packaging waste in most simulated scenarios, the waste-increasing outcome in Proposition 2 occurs with nonnegligible frequency under calibrated parameter values. The monotone pattern also suggests that this backfire

effect deserves greater attention in settings where disposable packaging is relatively costly.

Finally, we examine the environmental implications of improving the convenience of firm-owned reusable packaging. We regenerate scenarios for all model parameters (except for h_f) based on the distributions described at the beginning of this section. In each scenario, for any given hassle cost h_f, we compute the firm's optimal decisions: p_d^b, p_c^b, p_d^f, p_c^f, p_f^f, and f^f. We then conduct an exhaustive search and evaluate W^f over the following grid of h_f values: $\{h_f = 0.1 + 0.001(i-1)\}_{i=1}^{251} \triangleq \mathbb{G}_f$. After applying the model assumptions as before, we generate 100,000 scenarios. In Proposition 4(ii), we identified h_c as a conditioning variable, with the result holding when h_c is large. Then, for each of the following three ranges of h_c: $[0.15, 0.25)$, $[0.25, 0.35)$, and $[0.35, 0.4]$, we compute the proportion of scenarios in which the counterintuitive outcome in Proposition 4(ii) occurs; that is, there exists a pair of hassle costs for firm-owned reusable packaging such that the firm introduces its reusable packaging at both values, yet the average packaging waste per unit of product sold strictly increases in response to the lower hassle cost (i.e., $\exists\, h_{f1} < h_{f2} \in \mathbb{G}_f$ such that $\min(\pi^f(h_{f1}), \pi^f(h_{f2})) > \pi^b$ and $W^f(h_{f1}) > W^f(h_{f2})$). The corresponding proportions are 0.0%, 3.9%, and 21.5%, respectively. The increasing pattern shows that this counterintuitive result is more likely to occur when h_c is large. This finding indicates that convenience improvements for firm-owned reusable packaging require particular caution when personal reusable packaging remains inconvenient. Under this condition, consumers may be more likely to switch from the consumer-owned option to the firm-owned option, while the firm-owned option still carries non-return risk.

7 Discussions and Conclusions

Achieving a successful transition from traditional disposable packaging to reusable alternatives is critical for reducing packaging waste and the resulting environmental impact. However, this transition is especially challenging in the takeaway food and beverage sector (e.g., coffee chains), where firm-owned reusable packaging schemes (e.g., borrow-and-return cup programs) and consumer-owned reuse options (e.g., bring-your-own-cup programs) are often both feasible and can coexist as alternatives to disposable packaging. This paper examines how consumers choose among disposable packaging, consumer-owned reusable packaging, and firm-owned reusable packaging in response to perceived inconvenience and price incentives. Our analysis shows how substitution dynamics between consumer-owned and firm-owned reuse options create an inherent tension between profitability and packaging waste reduction, thereby clarifying the implications of firm-owned reusable packaging programs when consumers can also use their own reusable packaging.

First, firms should manage firm-owned and consumer-owned reusable packaging jointly rather than as independent sustainability initiatives. The growth of the eco-conscious market alone should not be viewed as sufficient justification for introducing a firm-owned reusable option. Although a more eco-conscious market implies stronger demand for reuse, it may also weaken the price-discrimination benefit of the firm-owned reusable option. Thus, firms should evaluate whether firm-owned reusable packaging (e.g., a borrow-and-return cup program) creates sufficient incremental value beyond existing consumer-owned reuse (e.g., a bring-your-own-cup program). Regarding convenience improvements, firms should be cautious when making the return process of firm-owned reusable packaging more convenient, for example by adding return bins or expanding return locations. Although such improvements can reduce the price discounts required to compensate consumers for return hassle, they may also induce some consumers to switch from the consumer-owned option to the firm-owned option. This behavioral response can increase packaging waste because firm-owned reusable packaging remains subject to non-return risk.

Second, governments and third-party organizations that evaluate or shape reusable packaging programs should not treat the introduction of firm-owned reusable packaging as inherently waste-reducing. This is particularly important when disposable packaging is costly to offer, as may occur under regulations such as plastic taxes and extended producer responsibility requirements (Cartwright, 2025). In such settings, a profit-driven firm may offer a large price incentive to encourage consumer-owned reuse in the absence of firm-owned reusable packaging. However, when the firm finds it profitable to offer firm-owned reusable packaging, it may reduce the discount for consumer-owned reuse to save on incentive costs. Such reductions can discourage reuse adoption among eco-unconscious consumers and, in turn, increase overall packaging waste. Thus, program evaluations should account for whether firm-owned reuse weakens existing bring-your-own incentives, rather than focusing only on the availability of the firm-owned option.

There are some other interesting related topics that are worth exploring in the future. First, this paper focuses on monetary (price-based) incentives as a mechanism to help consumers overcome the hassle associated with using reusable packaging, given that such incentives are the most widely implemented in practice. Nevertheless, in addition to monetary incentives, firms are increasingly experimenting with pro-environmental incentives as alternatives to monetary incentives to encourage pro-environmental consumer behavior. For instance, over 180 hotels have partnered with Hotels for Trees to plant a tree whenever guests skip daily room cleaning, thereby saving water and energy (Seo, 2023). This opens up an intriguing avenue for future research to examine the relative effectiveness of

these two types of incentives in driving the adoption of reusable packaging. Second, according to Ellen Macarthur Foundation (2019), there are four types of business-to-consumer reuse models: (i) refill at home (i.e., consumers refill their reusable container at home), (ii) refill on the go (i.e., consumers refill their reusable container away from home), (iii) return from home (i.e., packaging is picked up from home by a pickup service), and (iv) return on the go (i.e., consumers return the packaging at a store or drop-off point). Our current analysis in this paper can capture some of these models; for example, consumers can use their personal reusable packaging to buy the product and the firm can choose to offer reusable packaging which needs to be returned by consumers after each use. It would be an interesting future research topic to incorporate all four above-mentioned reuse models in a more detailed fashion and study the nuances between all of them. Finally, this paper does not explicitly analyze government decisions, even though they play a crucial role in balancing conflicts of interest among various stakeholders and the environment (Yu et al., 2018; Zhang and Dou, 2022; Yang et al., 2024). This presents an opportunity for future research to examine how different government policies, such as a disposable packaging tax, affect firms' packaging strategies and consumer reuse adoption. We hope that our model in this paper could motivate more research in the fields of pro-environmental behavior and circular business models.

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Appendix A Notations

Decision Variables	
p_d	price of the product with disposable packaging
p_c	price of the product with consumer-owned reusable packaging
p_f	price of the product with firm-owned reusable packaging
f	deposit for firm-owned reusable packaging
Parameters	
v	consumer valuation of the main product
α	fraction of eco-conscious consumers in the market
θ	fraction of packaging-independent consumers (i.e., those who have personal reusable packaging immediately accessible at the time of purchase) in the market
β	probability of being in the effortless-return state after borrowing reusable packaging
ξ	disutility that eco-conscious consumers incur when packaging waste is generated
c_d	unit cost of disposable packaging
$c_{r,m}$	unit procurement cost of firm-owned reusable packaging
$c_{r,o}$	unit operational cost of managing returned firm-owned reusable packaging
k	hassle cost of retrieving personal reusable packaging for packaging-dependent consumers
h_c	hassle cost of using personal reusable packaging
$\Phi \in \{1, \phi\}$	state-dependent cost-perception coefficient for packaging return
h_f	baseline hassle cost of returning firm-owned reusable packaging
T	maximum number of use cycles of firm-owned reusable packaging
Auxiliary Variables	
j	consumer type index, $j \in \{\text{CI}, \text{CD}, \text{UI}, \text{UD}\}$
$u_{D,j}$	utility of type-j consumers from purchasing the product with disposable packaging
$u_{C,j}$	utility of type-j consumers from purchasing the product with consumer-owned reusable packaging
$u_{F,j}$	utility of type-j consumers from purchasing the product with firm-owned reusable packaging
$d_{D,j}$	demand of type-j consumers using disposable packaging
$d_{C,j}$	demand of type-j consumers using consumer-owned reusable packaging
$d_{F,j}$	demand of type-j consumers using firm-owned reusable packaging
d_D	total demand using disposable packaging
d_C	total demand using consumer-owned reusable packaging
d_F	total demand using firm-owned reusable packaging
$d_{F,r}$	demand using firm-owned reusable packaging and returning it
$d_{F,u}$	demand using firm-owned reusable packaging and not returning it
ρ_c	probability that eco-conscious consumers return firm-owned reusable packaging
ρ_u	probability that eco-unconscious consumers return firm-owned reusable packaging
ρ	overall return rate of firm-owned reusable packaging
τ	expected number of use cycles of firm-owned reusable packaging
c_r	average cost per use of firm-owned reusable packaging
π	firm's profit
W	average packaging waste per unit of product sold

Online Appendix to

"Towards Reuse: The Implications of Price Incentives and Convenience of Reusable Packaging"

Yunlong Peng, Fei Gao, Jian Chen

In this Online Appendix, we present the details of model extensions with heterogeneous hassle costs and heterogeneous environmental impacts of packaging waste, the details of model calibration, and the proofs for the main model. Additional analyses and proofs, including the model extension with crowding-out effects, extensions with heterogeneous valuation and heterogeneous environmental disutility, and the proofs of all extended models, are provided in the Online Supplement.

For ease of exposition, throughout the Online Appendix and Online Supplement, we use u_j to denote the overall purchase utility of type-j consumers, where $j \in \{CI, CD, UI, UD\}$. Accordingly, in the benchmark model without firm-owned reusable packaging, $u_j = \max\{u_{D,j}, u_{C,j}\}$; in the model with firm-owned reusable packaging, $u_j = \max\{u_{D,j}, u_{C,j}, u_{F,j}\}$.

Online Appendix I Heterogeneous Hassle cost

In this section, we consider the case where eco-unconscious consumers incur a higher hassle cost $h_c + a$, with $a > 0$, when using personal reusable packaging. The hassle cost of eco-conscious consumers remains h_c.

The utility functions of eco-conscious consumers, including type-CI and type-CD consumers, are the same as in the main model. In contrast, the utility functions of eco-unconscious consumers are modified as follows:

- Without firm-owned reusable packaging:

$$u_{UI} = \max(v - p_d,\ v - h_c - a - p_c)$$
$$u_{UD} = \max(v - p_d,\ -k + v - h_c - a - p_c)$$

- With firm-owned reusable packaging:

$$u_{UI} = \max(v - p_d,\ v - h_c - a - p_c,\ v - p_f - \mathbb{E}[\min(\Phi h_f, f)])$$
$$u_{UD} = \max(v - p_d,\ -k + v - h_c - a - p_c,\ v - p_f - \mathbb{E}[\min(\Phi h_f, f)])$$

Note that our main model is a special case of $a = 0$.

We first look at the equilibrium outcome in the benchmark model without firm-owned reusable packaging.

Lemma OA.I.1. *In the benchmark model,*

(1) If $a < k$, there exist threshold functions $\bar{\mathcal{C}}_1^b(v, \alpha, \theta, h_c, \xi, k, a)$ and $\bar{\mathcal{C}}_2^b(v, \alpha, \theta, h_c, \xi, k, a)$ such that:

(i) If $c_d \le \min((h_c - \xi)^+, \bar{\mathcal{C}}_1^b)$, then $p_d^b = v - \xi$, $p_c^b = v - \xi$.

(ii) If $(h_c - \xi)^+ < c_d \le \bar{\mathcal{C}}_1^b$, then $p_d^b = v - \xi$, $p_c^b = v - \max(\xi, h_c)$.

(iii) If $\bar{\mathcal{C}}_1^b < c_d \le \bar{\mathcal{C}}_2^b$ and $k < \min(\alpha(1-\theta)(v - h_c) + (1-\alpha)a, \xi + a)$, then $p_d^b = v - k + a$, $p_c^b = v - k - h_c$.

(iv) If $\bar{\mathcal{C}}_1^b < c_d \le \bar{\mathcal{C}}_2^b$ and $k \ge \min(\alpha(1-\theta)(v - h_c) + (1-\alpha)a, \xi + a)$, then $p_d^b = v$, $p_c^b = v - h_c$.

(v) If $c_d > \bar{\mathcal{C}}_2^b$, then $p_d^b = v$, $p_c^b = v - k - h_c$.

(2) If $a \ge k$, there exists a threshold function $\mathcal{C}_3^b(v, \alpha, \theta, h_c, \xi, k)$ such that:

(i) If $c_d \leq \min((h_c - \xi)^+, \mathcal{C}_3^b)$, *then* $p_d^b = v - \xi$, $p_c^b = v - \xi$.
(ii) If $(h_c - \xi)^+ < c_d \leq \mathcal{C}_3^b$, *then* $p_d^b = v - \xi$, $p_c^b = v - \max(h_c, \xi)$.
(iii) If $c_d > \mathcal{C}_3^b$ *and* $k \leq (1-\theta)(v - h_c)$, *then* $p_d^b = v$, $p_c^b = v - k - h_c$.
(iv) If $c_d > \mathcal{C}_3^b$ *and* $k > (1-\theta)(v - h_c)$, *then* $p_d^b = v$, $p_c^b = v - h_c$.

We find that if $a < k$, the equilibrium outcome has the same structure as in Lemma 2. The only difference is that the firm is able to increase the price in strategy (iii) from $p_d^b = v - k$ (as in Lemma 2) to $p_d^b = v - k + a$.

Next, we look at the equilibrium outcome in the model with firm-owned reusable packaging. As shown in the proof of Lemma 3, the firm will always induce eco-unconscious consumers to use disposable packaging (i.e., $p_d \leq \min(p_f + \mathbb{E}[\min(\Phi h_f, f)], p_c + h_c + k + a)$ and $p_c \geq p_d - h_c - a$) to maximize its profit. Therefore, the presence of a does not affect the equilibrium outcome, leading to the same result as in Lemma 3.

Hence, if $a < k$, the result in Proposition 1 remains unchanged, except that the condition $c_d < \mathcal{C}_1^b$ is replaced by $c_d < \bar{\mathcal{C}}_1^b$, where $\bar{\mathcal{C}}_1^b$ is defined in Lemma OA.I.1. Similarly, the result in Proposition 2 remains unchanged, except that the condition $c_d > \mathcal{C}_2^b$ is replaced by $c_d > \bar{\mathcal{C}}_2^b$, where $\bar{\mathcal{C}}_2^b$ is defined in Lemma OA.I.1. The result in Propositions 3 and 4, both of which are based on the equilibrium outcome with firm-owned reusable packaging, remain unchanged.

Online Appendix II Heterogeneous Environmental Impacts of Packaging Waste

In the main model, we assume that eco-conscious consumers incur the same disutility, ξ, for generating packaging waste, regardless of the type of the packaging. This applies to both (i) using disposable packaging and (ii) failing to return firm-owned reusable packaging, in which case the packaging exits the reuse loop and needs to be replaced with new packaging. Consistent with this assumption, when evaluating environmental impact, our metric of "average packaging waste per unit of product sold" treats these two waste streams equivalently by simply summing them.

In this section, we extend the model to incorporate heterogeneity in the environmental impacts of these two distinct packaging waste sources. Specifically, let $e_d > 0$ denote the environmental impact generated by disposable packaging waste, and $e_r > 0$ denote the environmental impact generated when firm-owned reusable packaging is not returned.

We assume that eco-conscious consumers incur a disutility λ for *each unit* of environmental impact caused by packaging waste. Consequently, the total disutility incurred from using disposable packaging is defined as $\xi_d = \lambda e_d$, and the resulting utility derived from purchasing a product with disposable packaging is:

$$v - \xi_d - p_d \tag{OA.II.1}$$

Accordingly, the disutility incurred from failing to return firm-owned reusable packaging is $\xi_r = \lambda e_r$. The resulting expected utility from purchasing the product with firm-owned reusable packaging is given by:

$$v - f - p_f + \mathbb{E}_\Phi[\max(f - \Phi h_f, -\xi_r)] = v - p_f - \mathbb{E}_\Phi[\min(\Phi h_f, f + \xi_r)] \tag{OA.II.2}$$

The main model corresponds to the special case where $e_d = e_r$ (implying $\xi_d = \xi_r = \xi$).

Accordingly, we redefine the environmental metric as follows:

$$E \triangleq \text{average environmental impact per unit of product sold} \tag{OA.II.3}$$

In the model without firm-owned reusable packaging, $E^b = \frac{e_d d_D^b}{d_D^b + d_C^b}$; in the model with firm-owned reusable packaging, we have $E^f = \frac{e_d d_D^f + e_r d_{F,u}^f}{d_D^f + d_F^f + d_C^f}$. Note that the main model corresponds to the special case where $e_d = e_r$ and $W = E/e_d$.

Lemma OA.II.1. *In the benchmark model, there exist thresholds $\tilde{\mathcal{C}}_1^b(v, \alpha, \theta, h_c, \xi_d, k)$ and $\tilde{\mathcal{C}}_2^b(v, \alpha, \theta, h_c, \xi_d, k)$ such that:*

(i) If $c_d \le \min((h_c - \xi_d)^+, \tilde{\mathcal{C}}_1^b(\cdot))$, then $p_d^b = v - \xi_d$, $p_c^b = v - \xi_d$.
(ii) If $(h_c - \xi_d)^+ < c_d \le \tilde{\mathcal{C}}_1^b(\cdot)$, then $p_d^b = v - \xi_d$, $p_c^b = v - \max(\xi_d, h_c)$.
(iii) If $\tilde{\mathcal{C}}_1^b(\cdot) < c_d \le \tilde{\mathcal{C}}_2^b(\cdot)$ and $k < \min(\alpha(1-\theta)(v - h_c), \xi_d)$, then $p_d^b = v - k$, $p_c^b = v - h_c - k$.
(iv) If $\tilde{\mathcal{C}}_1^b(\cdot) < c_d \le \tilde{\mathcal{C}}_2^b(\cdot)$ and $k \ge \min(\alpha(1-\theta)(v - h_c), \xi_d)$, then $p_d^b = v$, $p_c^b = v - h_c$.
(v) If $c_d > \tilde{\mathcal{C}}_2^b(\cdot)$, then $p_d^b = v$, $p_c^b = v - h_c - k$.

Compared with Lemma 2, Lemma OA.II.1 shows that the benchmark model without firm-owned reusable packaging remains structurally unchanged; we simply replace ξ with ξ_d.

Proposition OA.II.1. *(i) The firm will offer firm-owned reusable packaging (i.e., $\pi^f > \pi^b$) if and only if $c_{r,o} < \tilde{\mathcal{C}}^f(c_d, v, \alpha, \theta, \beta, \phi, h_c, h_f, \xi_d, \xi_r, k, c_{r,m}, T)$ for some threshold $\tilde{\mathcal{C}}^f(\cdot)$.*

(ii) When the cost of disposable packaging is small, there are instances in which the firm offers firm-owned reusable packaging for a small fraction of eco-conscious consumers, but not for a large fraction. (Formally, if $c_d < \tilde{\mathcal{C}}_1^b(\cdot)$, where $\tilde{\mathcal{C}}_1^b$ is defined in Lemma OA.II.1, then there exist $\alpha_1 < \alpha_2$ such that $c_{r,o} < \tilde{\mathcal{C}}^f\big|_{\alpha=\alpha_1}$ and $c_{r,o} > \tilde{\mathcal{C}}^f\big|_{\alpha=\alpha_2}$.)

Lemma OA.II.2. *There exist thresholds $\tilde{\mathcal{H}}_c(\alpha, \theta, \beta, \phi, \xi_r, c_{r,o}, c_{r,m}, T, h_f)$, $\tilde{\mathcal{H}}_{f1}(\alpha, \theta, \beta, \phi, \xi_r, c_{r,o}, c_{r,m}, T)$ and $\tilde{\mathcal{H}}_{f2}(\alpha, \theta, \beta, \phi, \xi_r, c_{r,o}, c_{r,m}, T)$ such that the firm's optimal pricing strategy is as follows:*

(a) If $h_c < \tilde{\mathcal{H}}_c(\cdot)$ and $h_f \ge \tilde{\mathcal{H}}_{f1}(\cdot)$, then $p_d^f = v - (1-\beta)\xi_r$, $p_c^f = \min(v - (1-\beta)\xi_r, v - h_c)$, $p_f^f = v - h_f - (1-\beta)\xi_r$, and $f^f = h_f$.
(b) If $h_c < \tilde{\mathcal{H}}_c(\cdot)$ and $h_f < \tilde{\mathcal{H}}_{f1}(\cdot)$, then $p_d^f = v$, $p_c^f = v - h_c$, $p_f^f = v - (\beta + (1-\beta)\phi)h_f$, and $f^f = \phi h_f$.
(c) If $h_c \ge \tilde{\mathcal{H}}_c(\cdot)$ and $h_f \ge \tilde{\mathcal{H}}_{f2}(\cdot)$, then $p_d^f = v - (1-\beta)\xi_r$, $p_c^f = v - (1-\beta)\xi_r$, $p_f^f = v - h_f - (1-\beta)\xi_r$, and $f^f = h_f$.
(d) If $h_c \ge \tilde{\mathcal{H}}_c(\cdot)$ and $h_f < \tilde{\mathcal{H}}_{f2}(\cdot)$, then $p_d^f = v$, $p_c^f = v$, $p_f^f = v - (\beta + (1-\beta)\phi)h_f$, and $f^f = \phi h_f$.

Based on Proposition OA.II.1 and Lemma OA.II.2, we can find that the equilibrium outcomes of the model with firm-owned reusable packaging also remain unchanged, with the only modification being the replacement of ξ by ξ_r. Furthermore, the key insight of Proposition 1 that a larger α could discourage the firm from introducing its reusable packaging is still valid.

Proposition OA.II.2. *Compared to the benchmark model, when the firm chooses to offer its reusable packaging, $E^f > E^b$ if $c_d > \tilde{\mathcal{C}}_2^b(\cdot)$, where $\tilde{\mathcal{C}}_2^b(\cdot)$ is defined in Lemma OA.II.1.*

Proposition OA.II.2 shows that the key insight of Proposition 2, that the introduction of firm-owned reusable packaging may lead to greater environmental impact due to packaging waste, remains valid.

Proposition OA.II.3. *When the firm offers its reusable packaging,*

(i) A decrease in the hassle of consumer-owned reusable packaging always increases the profit. (Formally, π^f is decreasing in h_c.)

(ii) A decrease in the hassle of firm-owned reusable packaging always increases the profit. (Formally, π^f is decreasing in h_f.)

Proposition OA.II.3 confirms the result shown in Proposition 3, i.e., improving the convenience of reusable packaging (either consumer-owned or firm-owned) has a positive impact on the firm's profit.

Proposition OA.II.4. *When the firm offers its reusable packaging,*

(i) A decrease in the hassle of consumer-owned reusable packaging always reduces the average environmental impact per unit of product sold. (Formally, E^f is weakly increasing in h_c.)

(ii) There are instances where the average environmental impact per unit of product sold increases as the hassle of using firm-owned reusable packaging decreases, particularly when using consumer-owned reusable packaging is not very convenient. (Formally, there exist h_{f1}, h_{f2} such that $\tilde{\mathcal{H}}_{f2} < h_{f1} < h_{f2}$ and $E^f|_{h_f=h_{f1}} > E^f|_{h_f=h_{f2}}$ if $h_c > \tilde{\mathcal{H}}^*(\cdot)$ for some threshold $\tilde{\mathcal{H}}^*(\alpha, \theta, \beta, \phi, \xi_r, c_{r,o}, c_{r,m}, T)$, where $\tilde{\mathcal{H}}_{f2}$ is defined in Lemma OA.II.2).

Proposition OA.II.4 shows that the result of Proposition 4 still holds, i.e., improving the convenience of consumer-owned reusable packaging always reduces environmental impact, while improving the convenience of firm-owned reusable packaging could increase the environmental impact.

Online Appendix III Model Calibration

In this section, we provide the detailed justification and empirical evidence supporting the parameter values used in Section 6 of the main paper.

- $T \sim U(20, 40)$: A proper mean of the designed lifespan is 30. For example, the reusable cups offered by Starbucks' "Borrow A Cup" program are tested to last for up to 30 uses (Starbucks, 2021).
- $\beta \sim U(0.5, 0.9)$: In our model, the resulting return rate is $\rho \in \{\beta, 1\}$ in equilibrium. The range $(0.5, 0.9)$ for β in our model reflects the return rates observed in recent real-world initiatives. For example, reusable takeaway cup pilot programs led by companies such as Coca-Cola, Starbucks, and PepsiCo achieved a return rate of 51% (Packaging Europe, 2025). The Return-to-Earn scheme at UCL East recorded a 79% return rate following its trial (UCL, 2025), while a reusable cup program in a Danish city reached an 85% return rate (Jones, 2024).
- $c_d \sim U(0.05, 0.15)$: The unit purchase cost of disposable cups is typically on the order of 5–15 euro cents (McKinsey & Company, 2023).
- $c_{r,m} \sim U(0.3, 0.7)$: A reasonable mean value for $c_{r,m}$ is 0.5, which is 5 times the mean of c_d. According to cost estimates from Eunomia (2024), the average purchase costs of a reusable plastic cup and a single-use cup are 50 euro cents and 11 euro cents, respectively.

- $c_{r,o} \sim U(0.1, 0.2)$: A reasonable mean for $c_{r,o}$ is 0.15, which is 1.5 times the disposable packaging's average cost c_d. According to cost estimates from McKinsey & Company (2023), the operational cost (including transportation and cleaning) is around 160% of the disposable packaging cost. If economies of scale can be achieved in a centralized reuse system, the operational cost can be reduced to EUR 0.1 (Eunomia, 2024), which is the same as the average cost of a disposable cup. Therefore, the proper lower bound is 0.1.
- $v \sim U(0.8, 1.2)$: A reasonable mean for v is 1, given that the mean for c_d is 0.1. In our model, $v - c_d$ represents the unit margin that the firm can extract from eco-unconscious consumers. Thus, the implied profit-to-cost ratio is $(v - c_d)/c_d = 9$. This aligns with the actual financial performance of the coffee industry. For instance, using 2024 Starbucks data (Kerr, 2024; Starbucks, 2024), an average price of \$5.00 combined with a 15% operating margin implies a unit marginal profit of \$0.75 (corresponding to $v - c_d$ in our model). Comparing this to Starbucks' disposable cup cost of \$0.08 (Benaroya, 2019) (corresponding to c_d) yields a real-world profit-to-cost ratio of approximately 9. This empirical evidence supports our parameterization of $v - c_d \approx 9c_d$.
- $\alpha \sim U(0.2, 0.6)$: A reasonable mean value for α would be 0.4, as 40% of consumers are considered as purpose-driven consumers and think that sustainability is very important for them (IBM, 2020). Specifically, for consumer goods, 25% of consumers think that sustainability is extremely important to them in their purchase decision (Simon-Kucher & Partners, 2021). Hence, a lower bound of 0.2 for α is appropriate. It is also reported that 55% of U.S. consumers are extremely or very concerned about the environmental impact of product packaging (McKinsey & Company, 2020). Therefore, an upper bound of 0.6 is appropriate.
- $\theta \sim U(0.4, 0.6)$: θ represents the fraction of consumers who have direct access to their personal reusable packaging at the time of purchase. Accordingly, $1 - \theta$ represents the fraction of consumers who forget to bring reusable packaging for shopping trips, or who decide to shop at a time when their reusable packaging is not on hand. A reasonable mean for θ is 0.5, as 44% of consumers cite difficulty remembering to bring reusable packaging as a barrier to adopting reusable systems (PA Consulting, 2024). Similarly, 55% of participants specifically mentioned forgetting the bottle as the biggest impediment to using reusable bottles (Putnam-Farr et al., 2023).
- $h_c \sim U(0.15, 0.4)$: A reasonable mean value for h_c is 0.27. In our model, h_c represents the perceived inconvenience of carrying and cleaning personal reusable packaging. Meanwhile, it also represents the minimum discount required to incentivize eco-unconscious consumers to adopt personal reusable packaging. Since we normalize the baseline cost of a disposable cup (c_d) to 0.1 (representing approximately 10 cents), a mean h_c of 0.27 corresponds to a monetary value of 27 cents. This calibration aligns with empirical findings by Nicolau et al. (2022), which indicate that a financial incentive of 27 cents is required to incentivize respondents to use their personal reusable cups.
- $\xi \sim U(0.15, 0.4)$: We calibrate the range of the psychological disutility of generating waste (ξ) to be comparable in magnitude to the hassle cost (h_c). Given this range, ξ can be either greater or smaller than h_c. This flexibility allows our model to capture the full spectrum of consumer heterogeneity, ranging from eco-driven individuals whose guilt outweighs the inconvenience of washing to convenience-oriented consumers who prioritize effort reduction.
- $h_f \sim U(0.1, 0.35)$: We assume the range of h_f is slightly lower than that of h_c. This reflects the fact that firm-owned packaging (h_f) eliminates the burden of cleaning associated with personal reusable

cups (h_c). However, our model maintains a flexible relationship between h_c and h_f. This accounts for factors such as hygiene concerns regarding shared packaging, which can elevate the perceived burden for some consumers despite the physical convenience (Cole, 2022).

- $k \sim U(0.15, 0.4)$: In our model, k represents the retrieval cost incurred when a consumer needs to fetch a container that was not immediately at hand. This parameter quantifies the physical effort associated with actions such as returning to an office or vehicle to retrieve the item. Note that both k and h_c fundamentally measure time-based physical frictions. Given the same range $[0.15, 0.4]$, k could be smaller or larger than h_c, which reflects scenarios where the detour to retrieve a reusable container is either marginally less or more burdensome than carrying and washing it.
- $\phi \sim U(7, 13)$: We set the mean of ϕ to 10. This magnitude ensures that returning the packaging represents a substantial burden for consumers when they are in the effortful-return state.

Online Appendix IV Proofs for the Main Model

Proof Lemma 1: When $\alpha = 0$, there are only eco-unconscious consumers in the market. Recall that $u_{UI} = \max(v - p_d, v - h_c - p_c)$ and $u_{UD} = \max(v - p_d, -k + v - h_c - p_c)$. Then, there are three pricing strategies.

- Set the price at $p_c = p_d = v$ such that all consumers use disposable packaging. The corresponding profit is $\pi = v - c_d$. In this case, $d_C = 0$.
- Set the price at $p_d = v, p_c = v - h_c$ such that type-UI consumers use personal reusable packaging and type-UD consumers use firm-owned disposable packaging. Then, the corresponding profit is $\pi = \theta(v - h_c) + (1 - \theta)(v - c_d)$. In this case, $d_C = \theta$.
- Set the price at $p_d > v$ and $p_c = v - h_c - k$ such that all consumers use personal reusable packaging. Then, the corresponding profit is $\pi = v - h_c - k$. In this case, $d_C = 1$.

Based on the comparison of the above three cases, we know that the firm will choose the first strategy such that $d_C = 0$ if and only if $c_d < h_c$. □

Proof of Lemma 2: Consumers' utility functions are as follows: $u_{CI} = \max(v - \xi - p_d, v - h_c - p_c)$, $u_{CD} = \max(v - \xi - p_d, -k + v - h_c - p_c)$, $u_{UI} = \max(v - p_d, v - h_c - p_c)$, $u_{UD} = \max(v - p_d, -k + v - h_c - p_c)$.

First, the firm never sets $p_c < p_d - h_c - k$ such that all consumers use consumer-owned reusable packaging, since it is always dominated by the case when $p_c = p_d - h_c - k$ such that type-UD consumers use disposable packaging and pay the full price p_d.

Second, we can find that type-CD consumers will use reusable packaging only if $p_d - p_c \geq h_c + k - \xi$, while type-UI consumers will use reusable packaging only if $p_d - p_c \geq h_c$. Then, type-CD consumers will require a smaller discount than type-UI consumers when $k < \xi$.

Then, the firm's optimal strategy can be chosen from:

(0) Sell to all consumers and do not induce any consumers to use personal reusable packaging. Then, the firm sets $p_d = v - \xi$, $p_c = v - \xi$. The corresponding profit is:

$$\pi_0 = v - \xi - c_d$$

Note that this case can hold only if $\xi < h_c$.

(1) Sell to all consumers and induce type-CI consumers to use reusable packaging. Then, the firm

sets $p_d = v - \xi$, $p_c = v - \max(h_c, \xi) = v - \xi - (h_c - \xi)^+$. The corresponding profit is

$$\pi_1 = \alpha\theta(v - \max(h_c, \xi)) + (1 - \alpha\theta)(v - \xi - c_d)$$

Note that this case can hold only if $\xi < k + h_c$.

(2) Sell to all consumers and induce type-CI, type-CD consumers to use reusable packaging. Then, the optimization problem is:

$$\begin{aligned} \max_{p_c, p_d} \ & \alpha p_c + (1 - \alpha)(p_d - c_d) \\ s.t. \ & p_c \le v - h_c - k \\ & p_c + h_c + k - \xi \le p_d \le p_c + h_c \\ & p_d \le v \end{aligned}$$

Then, the firm sets $p_d = v - k$, $p_c = v - k - h_c$. The corresponding profit is:

$$\pi_2 = \alpha(v - k - h_c) + (1 - \alpha)(v - k - c_d)$$

This case can hold only if $\xi > k$.

(3) Sell to type-CI, type-UI, and type-UD consumers and induce only type-CI consumers to use reusable packaging. Then, the firm should set $p_d = v$ and $p_c = v - h_c$. The corresponding profit is:

$$\pi_3 = \alpha\theta(v - h_c) + (1 - \alpha)(v - c_d)$$

(4) Sell to all consumers and induce type-CI, type-CD, type-UI consumers to use reusable packaging. Then, the firm should set $p_d = v$, $p_c = v - h_c - k$. The corresponding profit is:

$$\pi_4 = (\alpha + (1 - \alpha)\theta)(v - h_c - k) + (1 - \alpha)(1 - \theta)(v - c_d)$$

Observe that the marginal profits with respect to c_d satisfy $\frac{d\pi_0}{dc_d} < \frac{d\pi_1}{dc_d} < \frac{d\pi_2}{dc_d} = \frac{d\pi_3}{dc_d} < \frac{d\pi_4}{dc_d}$.

Comparing π_2 and π_3, we find that $\pi_2 > \pi_3$ if and only if $k < \alpha(1 - \theta)(v - h_c)$. Furthermore, Strategy 2 is feasible only if $k < \xi$. Accordingly, we define the boundary for the dominance of Strategy 2 as:

$$\mathcal{K}^b = \min(\alpha(1 - \theta)(v - h_c), \xi).$$

We define the critical cost thresholds as follows:

$$\begin{aligned} C_{1,1} &= \inf\{c_d \ge 0 \mid \max(\pi_2, \pi_4) \ge \max(\pi_0, \pi_1)\}, \\ C_{1,2} &= \inf\{c_d \ge 0 \mid \max(\pi_3, \pi_4) \ge \max(\pi_0, \pi_1)\}, \\ C_{2,1} &= \inf\{c_d \ge 0 \mid \pi_4 \ge \max(\pi_0, \pi_1, \pi_2)\}, \\ C_{2,2} &= \inf\{c_d \ge 0 \mid \pi_4 \ge \max(\pi_0, \pi_1, \pi_3)\}. \end{aligned}$$

Then, we obtain the unified thresholds:

$$\mathcal{C}_1^b = \begin{cases} C_{1,1} & \text{if } k < \mathcal{K}^b, \\ C_{1,2} & \text{if } k \ge \mathcal{K}^b, \end{cases} \quad \text{and} \quad \mathcal{C}_2^b = \begin{cases} C_{2,1} & \text{if } k < \mathcal{K}^b, \\ C_{2,2} & \text{if } k \ge \mathcal{K}^b. \end{cases}$$

Recall that $\pi_0 > \pi_1$ if and only if $c_d < (h_c - \xi)^+$. Based on the properties of the profit functions, the optimal strategy structure is characterized as follows:

- If $c_d \le \min((h_c - \xi)^+, \mathcal{C}_1^b)$, the firm chooses Strategy (0) and sets $p_d = v - \xi$, $p_c = v - \xi$.
- If $(h_c - \xi)^+ < c_d < \mathcal{C}_1^b$, the firm chooses Strategy (1) and sets $p_d = v - \xi$, $p_c = v - \max(\xi, h_c)$.

- If $\mathcal{C}_1^b < c_d < \mathcal{C}_2^b$, the firm chooses:
  - Strategy (2) (sets $p_d = v - k$, $p_c = v - k - h_c$) if $k < \mathcal{K}^b$;
  - Strategy (3) (sets $p_d = v$, $p_c = v - h_c$) if $k \geq \mathcal{K}^b$.
- If $c_d > \mathcal{C}_2^b$, the firm chooses Strategy (4) and sets $p_d = v$, $p_c = v - h_c - k$.

Note that since $c_d > 0$, the interval $(0, (h_c - \xi)^+)$ is empty if $h_c < \xi$. This leads to Lemma 2.

□

Proof of Proposition 1 and Lemma 3: In the model with firm-owned reusable packaging, consumers' utility functions are as follows:

$$\begin{aligned}
u_{CI} &= \max(v - \xi - p_d,\ v - h_c - p_c,\ v - p_f - \mathbb{E}[\min(\Phi h_f, f + \xi)]),\\
u_{CD} &= \max(v - \xi - p_d,\ -k + v - h_c - p_c,\ v - p_f - \mathbb{E}[\min(\Phi h_f, f + \xi)]),\\
u_{UI} &= \max(v - p_d,\ v - h_c - p_c,\ v - p_f - \mathbb{E}[\min(\Phi h_f, f)]),\\
u_{UD} &= \max(v - p_d,\ -k + v - h_c - p_c,\ v - p_f - \mathbb{E}[\min(\Phi h_f, f)]).
\end{aligned}$$

First, observe that the firm should always set $f \geq h_f - \xi$. Otherwise, no consumers would return the firm-owned packaging, which implies that firm-owned reusable packaging becomes a more costly version of disposable packaging (while also imposing disutility ξ on eco-conscious consumers). In that scenario, the model is strictly dominated by the benchmark model.

Next, let us refine consumers' packaging choices in the equilibrium where the firm offers firm-owned reusable packaging. Based on the utility functions, the conditions under which consumers prefer firm-owned reusable packaging to disposable packaging are:

- $p_d > p_f + \mathbb{E}[\min(\Phi h_f, f)]$ for eco-unconscious consumers;
- $p_d > p_f + \mathbb{E}[\min(\Phi h_f, f + \xi)] - \xi$ for eco-conscious consumers.

Note that $p_f + \mathbb{E}[\min(\Phi h_f, f)] > p_f + \mathbb{E}[\min(\Phi h_f, f + \xi)] - \xi$. Consequently, any strategy setting $p_d > p_f + \mathbb{E}[\min(\Phi h_f, f)]$ (where eco-unconscious consumers prefer firm-owned packaging) is dominated by setting $p_d = p_f + \mathbb{E}[\min(\Phi h_f, f)]$ (where they prefer disposable). This binding allows the firm to extract more surplus from eco-unconscious consumers. Thus, a profit-maximizing firm sets $p_d \leq p_f + \mathbb{E}[\min(\Phi h_f, f)]$, implying that only eco-conscious consumers are potential candidates for firm-owned reusable packaging.

To ensure adoption, the firm must set $p_f \leq \min(p_d + \xi,\ p_c + k + h_c,\ v) - \mathbb{E}[\min(\Phi h_f, f + \xi)]$ such that at least type-CD consumers choose firm-owned reusable packaging; otherwise, the demand for the firm's packaging is zero.

Given these conditions, type-CI consumers choose between firm-owned and personal reusable packaging, while type-UI and type-UD consumers choose between disposable and personal reusable packaging. The conditions under which these segments prefer personal reusable packaging are:

- $p_c \leq p_f + \mathbb{E}[\min(\Phi h_f, f + \xi)] - h_c$ for type-CI consumers. Note that $p_f + \mathbb{E}[\min(\Phi h_f, f + \xi)] - h_c > p_f + \mathbb{E}[\min(\Phi h_f, f)] - h_c \geq p_d - h_c$.
- $p_c < p_d - h_c$ for type-UI consumers.
- $p_c < p_d - h_c - k$ for type-UD consumers.

Any outcome with $p_d > p_c + h_c + k$ is dominated by $p_d = p_c + h_c + k$ (since $h_c + k > c_d$), allowing the firm to extract more surplus. Similarly, any outcome with $p_c < p_d - h_c$ is dominated by $p_c = p_d - h_c$

(since $h_c > c_d$).

Based on this analysis, if offering firm-owned packaging is profitable, the firm will sell to all consumers. Furthermore, the optimal strategy must fall into one of two cases regarding consumer segmentation:

(1) Induce type-CI to use personal reusable packaging (p_c), type-CD to use firm-owned reusable packaging (p_f), and all eco-unconscious consumers to use disposable packaging (p_d). The optimization problem is:

$$\max_{p_d,p_c,p_f,f} \pi = \alpha\theta p_c + \alpha(1-\theta)(p_f + f\mathbb{E}[I_{\Phi h_f > f+\xi}] - c_r(\rho(f))) + (1-\alpha)(p_d - c_d)$$
$$s.t.\ p_f \le v - \mathbb{E}[\min(\Phi h_f, f+\xi)]$$
$$\max(p_d - h_c, p_f + \mathbb{E}[\min(\Phi h_f, f+\xi)] - h_c - k) \le p_c \le \min(p_f + \mathbb{E}[\min(\Phi h_f, f+\xi)] - h_c, p_d)$$
$$\max(p_f, p_f + \mathbb{E}[\min(\Phi h_f, f+\xi)] - \xi) \le p_d \le p_f + \mathbb{E}[\min(\Phi h_f, f)]$$

where the indicator function $I_X = 1(=0)$ if X is true (false). The binding prices are $p_f = v - \mathbb{E}[\min(\Phi h_f, f+\xi)]$, $p_d = v - \mathbb{E}[\min(\Phi h_f, f+\xi)] + \mathbb{E}[\min(\Phi h_f, f)]$, and $p_c = \min(v - h_c, p_d)$. Regarding return behavior, there are two sub-cases:

(a) Effortless-return only: We require $f < \phi h_f - \xi$. The return rate is β, and the average cost is $c_r(\beta)$. Since the profit function is weakly increasing in f and constant for $f \in [h_f, \phi h_f - \xi]$, we set $f = h_f$. The corresponding profit is:

$$\pi_a = \alpha\theta \min(v-h_c, v-(1-\beta)\xi) + \alpha(1-\theta)(v - \beta h_f - (1-\beta)\xi - c_r(\beta)) + (1-\alpha)(v-(1-\beta)\xi - c_d)$$

(b) Full return: We require $f > \phi h_f - \xi$. The return rate is 1, with cost $c_r(1)$. The profit is increasing in f and constant for $f \ge \phi h_f$, so we set $f = \phi h_f$. The profit is:

$$\pi_b = \alpha\theta(v - h_c) + \alpha(1-\theta)(v - \beta h_f - (1-\beta)\phi h_f - c_r(1)) + (1-\alpha)(v - c_d)$$

(2) Sell to all consumers: Induce both type-CI and type-CD to use firm-owned reusable packaging (p_f), while type-UI and type-UD use disposable packaging (p_d).

$$\max_{p_d,p_c,p_f,f} \pi = \alpha(p_f + f\mathbb{E}[I_{\Phi h_f > f+\xi}] - c_r(\rho(f))) + (1-\alpha)(p_d - c_d)$$
$$s.t.\ p_f \le v - \mathbb{E}[\min(\Phi h_f, f+\xi)]$$
$$\max(p_f + \mathbb{E}[\min(\Phi h_f, f+\xi)] - h_c, p_d - h_c) < p_c \le p_d$$
$$\max(p_f, p_f + \mathbb{E}[\min(\Phi h_f, f+\xi)] - \xi) \le p_d \le p_f + \mathbb{E}[\min(\Phi h_f, f)]$$

This yields $p_d = p_f + \mathbb{E}[\min(\Phi h_f, f)]$ and $p_f = v - \mathbb{E}[\min(\Phi h_f, f+\xi)]$. There are two sub-cases for returns:

(c) Effortless-return only: Similar to (a), optimal $f = h_f$. The profit is:

$$\pi_c = \alpha(v - \beta h_f - (1-\beta)\xi - c_r(\beta)) + (1-\alpha)(v - (1-\beta)\xi - c_d)$$

Note that given the constraint that $p_d \ge p_c \ge p_f + \mathbb{E}[\min(\Phi h_f, f+\xi)]$, this case is feasible only if $h_c > (1-\beta)\xi$.

(d) Full return: Similar to (b), optimal $f = \phi h_f$. The profit is:

$$\pi_d = \alpha(v - \beta h_f - (1-\beta)\phi h_f - c_r(1)) + (1-\alpha)(v - c_d)$$

The firm's optimal profit is $\pi^f = \max(\pi_a, \pi_b, \pi_c, \pi_d)$, which is strictly decreasing in $c_{r,o}$. Since the benchmark profit $\pi^b = \max(\pi_0, \ldots, \pi_4)$ is independent of $c_{r,o}$, there exists a unique threshold $\mathcal{C}^f$

such that $\pi^f > \pi^b$ if and only if $c_{r,o} < \mathcal{C}^f$, defined as:

$$\mathcal{C}^f = \inf\{c_{r,o} \geq 0 \mid \pi^f \leq \pi^b\}.$$

This completes the proof of Proposition 1 (i).

Given the condition $c_{r,o} < \mathcal{C}^f$, we proceed to compare strategies (a), (b), (c), and (d).

Comparing strategies (a) and (b), observe that there exists a threshold $\mathcal{H}_{f1}$ such that $\pi_a > \pi_b$ if and only if $h_f > \mathcal{H}_{f1}$, where

$$\mathcal{H}_{f1} = \frac{(1-\alpha)(1-\beta)\xi + \alpha(1-\theta)(c_r(\beta) - c_r(1)) + \alpha\theta((1-\beta)\xi - h_c)^+}{\alpha(1-\theta)(1-\beta)\phi}.$$

Similarly, for strategies (c) and (d), there exists a threshold $\mathcal{H}_{f2}$ such that $\pi_c > \pi_d$ if and only if $h_f > \mathcal{H}_{f2}$, where

$$\mathcal{H}_{f2} = \frac{(1-\alpha)(1-\beta)\xi + \alpha(c_r(\beta) - c_r(1))}{\alpha(1-\beta)\phi}.$$

Comparing the two thresholds, it follows that $\mathcal{H}_{f1} > \mathcal{H}_{f2}$.

Next, we compare the optimal outcomes of the two main strategies. Note that $\max(\pi_a, \pi_b)$ is decreasing in h_c, while $\max(\pi_c, \pi_d)$ is independent of h_c. Therefore, there exists a threshold $\mathcal{H}_c$ such that $\max(\pi_a, \pi_b) > \max(\pi_c, \pi_d)$ if and only if $h_c < \mathcal{H}_c$. We define this threshold as:

$$\mathcal{H}_c = \inf\{h_c \geq 0 \mid \max(\pi_c, \pi_d) \geq \max(\pi_a, \pi_b)\}.$$

Furthermore, observe that $\pi_a > \pi_c$ if and only if $h_c < \beta h_f + (1-\beta)\xi + c_r(\beta)$. Consequently, when $h_f > \mathcal{H}_{f2}$, the condition $\mathcal{H}_c \geq \beta h_f + (1-\beta)\xi + c_r(\beta)$ always holds.

Summarizing the discussion above, we arrive at Lemma 3.

Finally, we give the proof of Proposition 1 (ii). Based on Lemma 2, when $c_d < \mathcal{C}_1^b$, the baseline profit is given by $\pi^b = v - \xi - c_d + \alpha\theta \max(0, \xi + c_d - \max(h_c, \xi))$.Next, we analyze the firm's profit under reusable packaging, denoted by $\pi^f = \max(\pi_a, \pi_b, \pi_c, \pi_d)$. We observe that for any strategy $k \in \{a, b, c, d\}$, the profit function can be decomposed into an affine function of α taking the form $\pi_k = g_{1,k} - \alpha g_{2,k}(c_{r,o})$. Here, $g_{1,k}$ is constant with respect to α and $c_{r,o}$, while $g_{2,k}(c_{r,o})$ is independent of α and strictly increasing in $c_{r,o}$. The specific coefficients for each strategy are derived as follows:

- Strategy (a): π_a implies $g_{1,a} = v - (1-\beta)\xi - c_d$ and $g_{2,a}(c_{r,o}) = \theta \max(h_c, (1-\beta)\xi) + (1-\theta)(\beta h_f + (1-\beta)\xi + c_r(\beta)) - (1-\beta)\xi - c_d$.
- Strategy (b): π_b implies $g_{1,b} = v - c_d$ and $g_{2,b}(c_{r,o}) = \theta h_c + (1-\theta)(\beta h_f + (1-\beta)\phi h_f + c_r(1)) - c_d$.
- Strategy (c): π_c implies $g_{1,c} = v - (1-\beta)\xi - c_d$ and $g_{2,c}(c_{r,o}) = \beta h_f + c_r(\beta) - c_d$.
- Strategy (d): π_d implies $g_{1,d} = v - c_d$ and $g_{2,d}(c_{r,o}) = \beta h_f + (1-\beta)\phi h_f + c_r(1) - c_d$.

The firm introduces reusable packaging if and only if $\pi^f > \pi^b$, where

$$\pi^f = \max\{\pi_a, \pi_b, \pi_c, \pi_d\}.$$

For each strategy $k \in \{a, b, c, d\}$,

$$\begin{aligned} \pi_k > \pi^b &\iff g_{1,k} - \alpha g_{2,k}(c_{r,o}) > v - \xi - c_d + \alpha\theta \max(0, \xi + c_d - \max(h_c, \xi)) \\ &\iff g_{2,k}(c_{r,o}) < \frac{g_{1,k} - (v - \xi - c_d)}{\alpha} - \theta \max(0, \xi + c_d - \max(h_c, \xi)). \end{aligned}$$

Moreover,

$$g_{1,k} - (v - \xi - c_d) = \begin{cases} \beta\xi, & k \in \{a, c\}, \\ \xi, & k \in \{b, d\}, \end{cases} > 0.$$

Because $g_{2,k}(c_{r,o})$ is strictly increasing in $c_{r,o}$, define

$$\mathcal{C}_k^f(\alpha) = g_{2,k}^{-1}\left(\frac{g_{1,k} - (v - \xi - c_d)}{\alpha} - \theta \max(0, \xi + c_d - \max(h_c, \xi))\right).$$

Because $g_{1,k} - (v - \xi - c_d) > 0$ and $g_{2,k}(c_{r,o})$ is strictly increasing in $c_{r,o}$, $\mathcal{C}_k^f(\alpha)$ is strictly decreasing in α. Moreover,

$$\begin{aligned} \pi^f > \pi^b &\iff \exists k \in \{a, b, c, d\} : \pi_k > \pi^b \\ &\iff c_{r,o} < \max_{k \in \{a,b,c,d\}} \mathcal{C}_k^f(\alpha). \end{aligned}$$

Therefore,

$$\mathcal{C}^f(\alpha) = \max_{k \in \{a,b,c,d\}} \mathcal{C}_k^f(\alpha),$$

which is strictly decreasing in α. Hence, for any $\alpha_1 < \alpha_2$,

$$\mathcal{C}^f|_{\alpha=\alpha_1} > \mathcal{C}^f|_{\alpha=\alpha_2}.$$

Then, choosing $c_{r,o}$ such that

$$\mathcal{C}^f|_{\alpha=\alpha_2} < c_{r,o} < \mathcal{C}^f|_{\alpha=\alpha_1}$$

yields an instance in which the firm introduces reusable packaging at α_1 but not at α_2.

Moreover, when $c_d < \mathcal{C}_1^b$, Lemma 2 gives $p_d^b = v - \xi$. Under strategies (a)–(d),

$$p_d^f \in \{v - (1 - \beta)\xi, v\} > v - \xi = p_d^b.$$

The corresponding consumer packaging choices follow directly from strategies (a)–(d) and Lemma 2, as summarized in Table 2. This completes the proof of Proposition 1(ii).

□

Proof of Proposition 2: In the benchmark model, according to the proof of Lemma 2, we know

- If $c_d < \min((h_c - \xi)^+, \mathcal{C}_1^b)$, then $W^b = 1$.
- If $(h_c - \xi)^+ < c_d < \mathcal{C}_1^b$, then $W^b = 1 - \alpha\theta$.
- If $\mathcal{C}_1^b < c_d \le \mathcal{C}_2^b$ and $k < \mathcal{K}^b$, then $W^b = 1 - \alpha$.
- If $\mathcal{C}_1^b < c_d \le \mathcal{C}_2^b$ and $k \ge \mathcal{K}^b$, then $W^b = \frac{1-\alpha}{1-\alpha+\alpha\theta}$
- If $c_d > \mathcal{C}_2^b$, then $W^b = (1 - \alpha)(1 - \theta)$.

We can find that W^b is weakly decreasing in c_d. Furthermore, $W^b < 1 - \alpha$ when $c_d > \mathcal{C}_2^b$.

In the model with firm-owned reusable packaging, according to the proof of Lemma 3, we know $W^f = 1-\alpha+\alpha(1-\theta)(1-\beta)$ under strategy (a); $W^f = 1-\alpha$ under strategy (b); $W^f = 1-\alpha+\alpha(1-\beta)$ under strategy (c); $W^f = 1 - \alpha$ under strategy (d).

Therefore, $W^f \ge 1 - \alpha$ always holds. Therefore, $W^f > W^b$ if $c_d > \mathcal{C}_2^b$.

□

Proof of Proposition 3: According to the proof of Lemma 3, we know strategy (c) is not available

when $h_c < (1-\beta)\xi$. Let $\pi_a, \pi_b, \pi_c, \pi_d$ denote the profit of the corresponding strategy (a), (b), (c) and (d), respectively. Then,

$$\pi^f = \begin{cases} \max(\pi_a, \pi_b, \pi_d) & \text{if } h_c < (1-\beta)\xi \\ \max(\pi_a, \pi_b, \pi_c, \pi_d) & \text{if } h_c \geq (1-\beta)\xi \end{cases}$$

We first look at the impact of h_c. According to the proof of Lemma 3, we know $\pi_a > \pi_c$ if and only if $h_c < (1-\beta)\xi + \beta h_f + c_r(\beta)$. Then,

- If $h_c < (1-\beta)\xi$, then $\pi^f = \max(\pi_a, \pi_b, \pi_d)$.
- If $(1-\beta)\xi \leq h_c < (1-\beta)\xi + \beta h_f + c_r(\beta)$, then $\pi^f = \max(\pi_a, \pi_b, \pi_c, \pi_d) = \max(\pi_a, \pi_b, \pi_d)$.
- If $h_c \geq (1-\beta)\xi + \beta h_f + c_r(\beta)$, then $\pi^f = \max(\pi_a, \pi_b, \pi_c, \pi_d)$

Therefore, π^f is a continuous function of h_c. Since $\pi_a, \pi_b, \pi_c, \pi_d$ are decreasing in h_c, we know π^f is also decreasing in h_c.

Then, we analyze the impact of h_f on π^f. Since π^f is always a continuous function of h_f and $\pi(a), \pi(b), \pi(c), \pi(d)$ are decreasing in h_f, we know π^f is decreasing in h_f. □

Proof of Proposition 4: We first look at the impact of h_c on W^f. According to the proof of Lemma 3, we know $\pi(a), \pi(b)$ are decreasing in h_c, while $\pi(c), \pi(d)$ are independent of h_c. Therefore, as h_c decreases, the firm might change from strategy (c) or (d) to strategy (a) or (b). The average packaging waste is $W(a) = 1-\alpha+\alpha(1-\theta)(1-\beta)$, $W(b) = 1-\alpha$, $W(c) = 1-\alpha+\alpha(1-\beta)$ and $W(d) = 1-\alpha$. Therefore, as h_c decreases, W^f might increase only if the firm changes from strategy (d) to strategy (a). However, we can find that $\pi(a) > \pi(b)$ if and only if $h_f > \mathcal{H}_{f1}$, while $\pi(d) > \pi(c)$ if and only if $h_f \leq \mathcal{H}_{f2}$. Since $\mathcal{H}_{f2} < \mathcal{H}_{f1}$, once the firm adopts strategy (d), the firm never changes to strategy (a) as h_c decreases. To sum up, we can find that W^f is weakly increasing in h_c.

Next, we look at the impact of h_f on W^f. According to the proof of Lemma 3, we know $\max(\pi(a), \pi(b)) > \max(\pi(c), \pi(d))$ if and only if $h_c < \mathcal{H}_c$.

Given the condition $h_c > (1-\beta)\xi$, we know $\mathcal{H}_{f1} = \frac{(1-\alpha)(1-\beta)\xi+\alpha(1-\theta)(c_r(\beta)-c_r(1))}{\alpha(1-\theta)(1-\beta)\phi}$, and $\mathcal{H}_{f2} = \frac{(1-\alpha)(1-\beta)\xi+\alpha(c_r(\beta)-c_r(1))}{\alpha(1-\beta)\phi}$. Recall that $\mathcal{H}_c$ is a function of h_f. Let $\mathcal{H}^* = \max(\mathcal{H}_c(h_f = \frac{(1-\alpha)(1-\beta)\xi+\alpha(c_r(\beta)-c_r(1))}{\alpha(1-\beta)\phi}), \mathcal{H}_c(h_f = \frac{(1-\alpha)(1-\beta)\xi+\alpha(1-\theta)(c_r(\beta)-c_r(1))}{\alpha(1-\theta)(1-\beta)\phi}), (1-\beta)\xi)$. Then, when $h_c > \mathcal{H}^*$, we know that $\max(\pi(c), \pi(d)) > \pi(b)$ always holds.

In addition, $\pi(a) > \pi(c)$ if and only if $h_f > \frac{h_c-(1-\beta)\xi-c_r(\beta)}{\beta}$. Furthermore, when $h_f > \mathcal{H}_{f2}$, we know $\pi(c) > \pi(d)$. Then, given $h_c > \mathcal{H}^*$, we can choose $h_{f2} > \frac{h_c-(1-\beta)\xi-c_r(\beta)}{\beta}$ and $\mathcal{H}_{f2} < h_{f1} < \frac{h_c-(1-\beta)\xi-c_r(\beta)}{\beta}$ such that the firm chooses strategy (a) when $h_f = h_{f2}$ and changes to strategy (c) when $h_f = h_{f1}$. In this way, when the return hassle decreases from h_{f2} to h_{f1}, the average packaging waste will increase from $W^f = 1-\alpha+\alpha(1-\theta)(1-\beta)$ to $W^f = 1-\alpha+\alpha(1-\beta)$.

□

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Online Supplement

In this Online Supplement, we provide additional analyses and proofs that are not included in the Online Appendix.

Online Supplement I Crowding-Out Effect of Price Incentives

In the main model, we assume that consumers respond equally to the price incentives $p_d - p_c$ (for consumer-owned reusable packaging) and $p_d - p_f$ (for firm-owned reusable packaging). However, for eco-conscious consumers, who are intrinsically motivated to engage in pro-environmental behavior to avoid the guilt associated with using disposable packaging, such monetary incentives may have a dual effect. While the discount reduces the effective price, it may also trigger a "crowding-out" effect, whereby extrinsic incentives diminish the internal satisfaction derived from acting in line with one's values. This phenomenon has been theoretically examined by Bénabou and Tirole (2006) and Bowles (2008), and empirically supported in the context of green goods consumption. For instance, based on field studies, both Perino et al. (2014) and Lanz et al. (2018) find that although price subsidies for low-emission products increase demand, they are less effective than neutrally framed price changes that do not communicate emission information. In the context of reusable packaging, Metta and Rousseau (2025) shows through a natural experiment that discounts do not significantly encourage consumers to bring their own coffee cups. These findings provide evidence of a crowding-out effect in price incentives aimed at encouraging pro-environmental behavior. Therefore, we should expect that price incentives may be less effective for eco-conscious consumers than for those without strong intrinsic environmental motivations (i.e., eco-unconscious consumers). In this section, we extend our main model to incorporate such a potential behavioral phenomenon.

Suppose the utility functions of eco-unconscious consumers remain the same as before. As for eco-conscious consumers, their utility functions need to be modified to reflect the crowding-out effect. Let $\gamma \in [0, 1]$ measure eco-conscious consumers' sensitivity to price incentives, which is attenuated by the crowding-out effect (Bénabou and Tirole, 2006; Perino et al., 2014). Then, eco-conscious consumers' utility functions are as follows.

- Without firm-owned reusable packaging:

$$u_{CI} = \max(v - \xi - p_d, v - h_c - p_d + \gamma(p_d - p_c))$$
$$u_{CD} = \max(v - \xi - p_d, -k + v - h_c - p_d + \gamma(p_d - p_c))$$

- With firm-owned reusable packaging:

$$u_{CI} = \max(v - \xi - p_d,\ v - h_c - p_d + \gamma(p_d - p_c),\ v - p_d + \gamma(p_d - p_f) - \mathbb{E}[\min(\Phi h_f, f + \xi)])$$
$$u_{CD} = \max(v - \xi - p_d,\ -k + v - h_c - p_d + \gamma(p_d - p_c),\ v - p_d + \gamma(p_d - p_f) - \mathbb{E}[\min(\Phi h_f, f + \xi)])$$

Note that our main model is a special case with $\gamma = 1$. The presence of the crowding-out effect makes it more difficult for the firm to use price discounts to incentivize eco-conscious consumers to adopt reusable packaging. This increased incentive cost can impact both the firm's profit and packaging waste.

We first derive the optimal pricing strategy for the model both with and without firm-owned reusable packaging in the presence of the crowding-out effect (i.e., $\gamma < 1$).

Lemma OS.I.1. *In the presence of the crowding-out effect, the optimal strategy in the benchmark model is selected from the following options:*

(b.0) $p_d = v - \xi$, $p_c = v - \xi$.

(b.1) $p_d = v - \xi$, $p_c = v - \xi - \frac{(h_c - \xi)^+}{\gamma}$.

(b.2) $p_d = v$, $p_c = v$.

(b.3) $p_d = v - h_c + \gamma \left(h_c I_{\gamma > \frac{\alpha\theta}{\alpha\theta+1-\alpha}} + \frac{(h_c-\xi)^+}{\gamma} I_{\gamma \leq \frac{\alpha\theta}{\alpha\theta+1-\alpha}} \right)$,

$p_c = v - h_c + (\gamma - 1) \left(h_c I_{\gamma > \frac{\alpha\theta}{\alpha\theta+1-\alpha}} + \frac{(h_c-\xi)^+}{\gamma} I_{\gamma \leq \frac{\alpha\theta}{\alpha\theta+1-\alpha}} \right)$.

(b.4) $p_d = v - k - h_c + \gamma \left(h_c I_{\gamma > \alpha} + \frac{(h_c+k-\xi)^+}{\gamma} I_{\gamma \leq \alpha} \right)$,

$p_c = v - k - h_c + (\gamma - 1) \left(h_c I_{\gamma > \alpha} + \frac{(h_c+k-\xi)^+}{\gamma} I_{\gamma \leq \alpha} \right)$.

(b.5) $p_d = v - h_c + \gamma \left(\min\left(\frac{h_c}{\gamma}, h_c + k\right) I_{\gamma > \frac{\theta}{\alpha\theta+1-\alpha}} + \max\left(h_c, \frac{h_c-\xi}{\gamma}\right) I_{\gamma \leq \frac{\theta}{\alpha\theta+1-\alpha}} \right)$,

$p_c = v - h_c + (\gamma - 1) \left(\min\left(\frac{h_c}{\gamma}, h_c + k\right) I_{\gamma > \frac{\theta}{\alpha\theta+1-\alpha}} + \max\left(h_c, \frac{h_c-\xi}{\gamma}\right) I_{\gamma \leq \frac{\theta}{\alpha\theta+1-\alpha}} \right)$.

(b.6) $p_d = v - k - h_c + \gamma \left(\frac{k+h_c}{\gamma} I_{\gamma > \alpha+(1-\alpha)\theta} + \max\left(h_c, \frac{k+h_c-\xi}{\gamma}\right) I_{\gamma \leq \alpha+(1-\alpha)\theta} \right)$,

$p_c = v - k - h_c + (\gamma - 1) \left(\frac{k+h_c}{\gamma} I_{\gamma > \alpha+(1-\alpha)\theta} + \max\left(h_c, \frac{k+h_c-\xi}{\gamma}\right) I_{\gamma \leq \alpha+(1-\alpha)\theta} \right)$.

Proposition OS.I.1.

(i) In the presence of the crowding-out effect, there exists a threshold function $\mathcal{C}^f(c_d, v, \alpha, \theta, \beta, \phi, h_c, h_f, \xi, k, c_{r,m}, T, \gamma)$ *such that it is profitable for the firm to introduce its reusable packaging if and only if* $c_{r,o} < \mathcal{C}^f(\cdot)$.

(ii) There exist $\alpha_1 < \alpha_2$ *such that* $c_{r,o} < \mathcal{C}^f|\alpha = \alpha_1$ *and* $c_{r,o} > \mathcal{C}^f|_{\alpha=\alpha_2}$ *when* $c_d < \mathcal{C}_1^b$ *for some* $\mathcal{C}_1^b$ *and* $\gamma > \Gamma_0^*$ *for some* Γ_0^*.

Proposition OS.I.1 shows that the key insight of Proposition 1 still holds, i.e., a larger α would discourage the firm from offering its reusable packaging.

Lemma OS.I.2. *When it is profitable for the firm to introduce its reusable packaging, the optimal pricing strategy is chosen from the following options:*

(f.1.1) The deposit $f = f_1$, *where* $f_1 = \arg \max_{\max(h_f - \xi, 0) \leq f \leq \phi h_f - \xi} [\alpha\theta p_{c1} + \alpha(1-\theta)(p_{f1} + (1-\beta)f - c_r(\beta)) + (1-\alpha)(p_{d1} - c_d)]$. *The prices are set as:*

$$p_d = p_{d1} = v - \mathbb{E}[\min(\Phi h_f, f + \xi)] + \gamma \Bigg[\min\left(\mathbb{E}[\min(\Phi h_f, f)], h_c - \frac{h_c - \mathbb{E}[\min(\Phi h_f, f + \xi)]}{\gamma} \right) I_{\gamma > \alpha}$$
$$+ \max\left((\frac{\mathbb{E}[\min(\Phi h_f, f + \xi)] - \xi}{\gamma})^+, \min\left(\frac{\mathbb{E}[\min(\Phi h_f, f + \xi)] - h_c}{\gamma}, \mathbb{E}[\min(\Phi h_f, f)] \right) \right) I_{\alpha(1-\theta) < \gamma \leq \alpha}$$
$$+ \left(\frac{\mathbb{E}[\min(\Phi h_f, f + \xi)] - \xi}{\gamma} \right)^+ I_{\gamma \leq \alpha(1-\theta)} \Bigg],$$
$$p_f = p_{f1} = \frac{1}{\gamma} \left(v - \mathbb{E}[\min(\Phi h_f, f + \xi)] - (1 - \gamma) p_{d1} \right),$$
$$p_c = p_{c1} = \min(p_{d1}, p_{f1} - \frac{h_c - \mathbb{E}[\min(\Phi h_f, f + \xi)]}{\gamma}).$$

(f.1.2) The deposit $f = \phi h_f$. *The prices* (p_d, p_f, p_c) *follow the same formulas as in (f.1.1) but with* $f = \phi h_f$.

(f.2.1) The deposit $f = f_2$, *where* $f_2 = \arg \max_{\max(h_f - \xi, 0) \leq f \leq \phi h_f - \xi} [\theta p_{c2} + \alpha(1-\theta)(p_{f2} + (1-\beta)f - c_r(\beta)) +$

$(1-\alpha)(1-\theta)(p_{d2}-c_d)]$. *The prices are set as:*

$$
\begin{aligned}
p_d = p_{d2} &= v - \mathbb{E}[\min(\Phi h_f, f+\xi)] + \gamma \Bigg[\mathbb{E}[\min(\Phi h_f, f)] I_{\gamma > \alpha+(1-\alpha)\theta} \\
&\quad + \max\left(\left(\frac{\mathbb{E}[\min(\Phi h_f, f+\xi)] - \xi}{\gamma} \right)^+, \min\left(\mathbb{E}[\min(\Phi h_f, f)], h_c - \frac{h_c - \mathbb{E}[\min(\Phi h_f, f+\xi)]}{\gamma} \right) \right) I_{\alpha(1-\theta) < \gamma \le \alpha+(1-\alpha)\theta} \\
&\quad + \left(\frac{\mathbb{E}[\min(\Phi h_f, f+\xi)] - \xi}{\gamma} \right)^+ I_{\gamma \le \alpha(1-\theta)} \Bigg], \\
p_f = p_{f2} &= \frac{1}{\gamma} \left(v - \mathbb{E}[\min(\Phi h_f, f+\xi)] - (1-\gamma) p_{d2} \right), \\
p_c = p_{c2} &= \min\left(p_{d2} - h_c, p_{f2} - \frac{h_c - \mathbb{E}[\min(\Phi h_f, f+\xi)]}{\gamma} \right).
\end{aligned}
$$

(f.2.2) The deposit $f = \phi h_f$. The prices (p_d, p_f, p_c) follow the same formulas as in (f.2.1) but with $f = \phi h_f$.

(f.3.1) The deposit $f = f_3$, where $f_3 = \arg \max_{\max(h_f-\xi,0) \le f \le \phi h_f - \xi} [\alpha(p_{f3} + (1-\beta)f - c_r(\beta)) + (1-\alpha)(p_{d3} - c_d)]$. The prices are set as:

$$
\begin{aligned}
p_d = p_{d3} &= v - \mathbb{E}[\min(\Phi h_f, f+\xi)] + \gamma \Bigg[\mathbb{E}[\min(\Phi h_f, f)] I_{\gamma > \alpha} \\
&\quad + \left(\frac{\mathbb{E}[\min(\Phi h_f, f)] - \xi}{\gamma} \right)^+ I_{\gamma \le \alpha} \Bigg], \\
p_f = p_{f3} &= \frac{1}{\gamma} \left(v - \mathbb{E}[\min(\Phi h_f, f+\xi)] - (1-\gamma) p_{d3} \right), \quad p_c = p_{d3}.
\end{aligned}
$$

(f.3.2) The deposit $f = \phi h_f$. The prices (p_d, p_f, p_c) follow the same formulas as in (f.3.1) but with $f = \phi h_f$.

Proposition OS.I.2. *Compared to the benchmark model, when the firm chooses to offer its reusable packaging, there exist threshold functions $\mathcal{C}^*(v, \alpha, \theta, \xi, h_c, k, \gamma)$, $\mathcal{H}^*(v, \alpha, \theta, \beta, \phi, h_c, h_f, \xi, k, c_{r,m}, T, \gamma)$ such that $W^f > W^b$ if $c_d > \mathcal{C}^*(\cdot)$, $h_c < \mathcal{H}^*(\cdot)$ and $\gamma > \max(\alpha + (1-\alpha)\theta, \frac{\theta}{\alpha\theta + 1 - \alpha})$.*

Proposition OS.I.2 confirms that the result in Proposition 2 still holds, i.e., the introduction of firm-owned reusable packaging could increase the average packaging waste.

Proposition OS.I.3. *When the firm offers its reusable packaging, a decrease in the hassle of consumer-owned reusable packaging always increases the profit. (Formally, π^f is decreasing in h_c).*

Proposition OS.I.3 shows that the result of Proposition 3(i) is still valid, i.e., improving the convenience of consumer-owned reusable packaging can always increase the profit.

Proposition OS.I.4. *When the firm offers reusable packaging, there are instances where the firm's profit decreases when the hassle of using firm-owned reusable packaging decreases, if the crowding-out effect is significant, and the operational cost of firm-owned reusable packaging is not too small. (Formally, when the firm offers reusable packaging, there exist $\tilde{h}_{f1} < \tilde{h}_{f2}$ such that $\pi^f|_{h_f = \tilde{h}_{f1}} < \pi^f|_{h_f = \tilde{h}_{f2}}$) if $\gamma < \Gamma_1^*(\cdot)$ and $c_{r,o} > \mathcal{C}_1^*$ for some $\Gamma_1^*(\alpha, \theta) < 1$ and $\mathcal{C}_1^*(\alpha, \theta, \beta, \phi, \xi, h_c, c_{r,m}, T, \gamma)$).*

In contrast to Proposition 3(ii), Proposition OS.I.4 shows that improving the convenience of firm-owned reusable packaging (h_f) can reduce the firm's profit when a significant crowding-out effect

is present. Specifically, when firm-owned reusable packaging is perceived as relatively inconvenient (i.e., $h_f = \tilde{h}_{f2}$), environmentally conscious type-CI consumers tend to use their personal reusable packaging. As the convenience of firm-owned reusable packaging improves (i.e., as h_f decreases from $\tilde{h}_{f2}$ to $\tilde{h}_{f1}$), firm-owned reuse becomes more attractive to type-CI consumers. In response to this shift in consumer preference, the firm faces two strategic responses: (i) increasing the discount for personal reusable packaging to induce type-CI consumers to continue using it, or (ii) inducing type-CI consumers to switch to firm-owned reusable packaging. When consumers are relatively insensitive to price discounts (i.e., $\gamma < \Gamma_1^*$), option (i) requires a substantial discount, leading to significantly higher incentive costs; moreover, a large discount for personal reusable packaging may attract type-UI consumers to switch from disposable packaging to exploit the discount, further increasing incentive costs. Alternatively, if the operational cost of firm-owned reusable packaging is high (i.e., $c_{r,o} > \mathcal{C}_1^*$), option (ii) results in a substantial increase in total packaging costs. Consequently, under either option, the firm's profitability is adversely affected.

Proposition OS.I.5. *When the firm offers reusable packaging, there are instances where average packaging waste per unit of product sold increases as the hassle of using personal reusable packaging decreases if the crowding-out effect is moderate and the disposable packaging cost is not too small. (Formally, there exists $h_{c1} < h_{c2}$ such that $W^f|_{h_c=h_{c1}} > W^f|_{h_c=h_{c2}}$ if $\Gamma_2^*(\cdot) < \gamma < \Gamma_3^*(\cdot)$ and $c_d > \mathcal{C}_2^*(\cdot)$ for some $\Gamma_2^*(\alpha,\theta), \Gamma_3^*(\alpha,\theta) < 1$ and $\mathcal{C}_2^*(\alpha,\theta,\beta,\phi,\xi,h_f,c_{r,m},c_{r,o},T,\gamma)$.)*

In contrast to Proposition 4(i), Proposition OS.I.5 shows that improving the convenience of consumer-owned reusable packaging can have negative environmental implications in the presence of significant crowding-out effect. The underlying mechanism is as follows. When the hassle of using personal reusable packaging is high (i.e., $h_c = h_{c2}$) and the cost of disposable packaging is also high (i.e., $c_d > \mathcal{C}_2^*$), the firm may consider incentivizing type-CI consumers to use their personal reusable packaging. However, due to the crowding-out effect (i.e., $\gamma < \Gamma_3^*$), the firm must offer a sufficiently large discount to make personal reusable packaging attractive. (Note that if the crowding-out effect is very strong, it becomes too costly for the firm to provide such an incentive, which leads to the condition $\gamma > \Gamma_2^*$.) This large discount also unintentionally attracts type-UI consumers to use their personal reusable packaging. As a result, all packaging-independent consumers (i.e., both type-CI and type-UI) adopt personal reusable packaging, and type-CD consumers adopt firm-owned reusable packaging, while only type-UD consumers use disposable packaging, leading to a low average packaging waste per unit of product sold.

As h_c decreases, personal reusable packaging becomes more convenient, making firm-owned reusable packaging less attractive to type-CI consumers. In response, the firm may *reduce* the discount for personal reusable packaging to cut costs. However, this reduced discount is insufficient to continue incentivizing type-UI consumers, who then switch to disposable packaging. Consequently, the number of consumers using disposable packaging increases, resulting in higher average packaging waste per unit of product sold.

Proposition OS.I.6. *When the firm offers its reusable packaging, there are instances where the average packaging waste per unit of product sold increases as the hassle of using firm-owned reusable packaging decreases, particularly when using consumer-owned reusable packaging is not very convenient*

and the crowding-out effect is not strong. (Formally, there exists h_{f1}, h_{f2} such that $h_{f1} < h_{f2}$ and $W^f|_{h_f=h_{f1}} > W^f|_{h_f=h_{f2}}$ if $h_c > \mathcal{H}^*(\cdot)$ for some threshold function $\mathcal{H}^*(\alpha, \theta, \beta, \phi, \xi, c_{r,m}, c_{r,o}, T, h_f, \gamma)$ and $\gamma > \Gamma_3^*$ for some $\Gamma_3^* < 1$.)

Proposition OS.I.6 shows that the result of Proposition 4(ii) still holds, i.e., improving the convenience of firm-owned reusable packaging could increase the average packaging waste per unit of product sold.

Online Supplement II Heterogeneous Valuation

In the main model, we assumed that consumers have a homogeneous valuation v for the main product. This assumption simplifies the analysis while allowing us to focus on other potentially more relevant dimensions of consumer heterogeneity, such as differences in environmental preferences and access to personal reusable packaging. In this subsection, we extend the model to incorporate heterogeneity in consumer valuation, denoted by V. Suppose V follows a general distribution with a cumulative distribution function $F(\cdot)$. The main model corresponds to the special case of $V = v$ with probability one. Consumers' utility functions remain the same as in the main model, except that we now replace v with V. Based on this extension, we derive the following demand functions.

- Without firm-owned reusable packaging:

$$d_{D,CI} = \begin{cases} \alpha\theta(1 - F(p_d + \xi)) & \text{if } p_d + \xi < p_c + h_c \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{D,CD} = \begin{cases} \alpha(1-\theta)(1 - F(p_d + \xi)) & \text{if } p_d + \xi < p_c + h_c + k \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{D,UI} = \begin{cases} (1-\alpha)\theta(1 - F(p_d)) & \text{if } p_d \le p_c + h_c \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{D,UD} = \begin{cases} (1-\alpha)(1-\theta)(1 - F(p_d)) & \text{if } p_d \le p_c + h_c + k \\ 0 & \text{otherwise.} \end{cases}$$

Given $d_{D,CI}, d_{D,CD}, d_{D,UI}, d_{D,UD}$, the total demand for product with disposable packaging is still given by Equation (6).

$$d_{C,CI} = \begin{cases} \alpha\theta(1 - F(p_c + h_c)) & \text{if } p_c + h_c \le p_d + \xi \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{C,CD} = \begin{cases} \alpha(1-\theta)(1 - F(p_c + h_c + k)) & \text{if } p_c + h_c + k \le p_d + \xi \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{C,UI} = \begin{cases} (1-\alpha)\theta(1-F(p_c+h_c)) & \text{if } p_c+h_c < p_d \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{C,UD} = \begin{cases} (1-\alpha)(1-\theta)(1-F(p_c+h_c+k)) & \text{if } p_c+h_c+k < p_d \\ 0 & \text{otherwise.} \end{cases}$$

Given $d_{C,CI}, d_{C,CD}, d_{C,UI}, d_{C,UD}$, the total demand for product with consumer-owned reusable packaging is still given by Equation (7).

- With firm-owned reusable packaging:

$$d_{D,CI} = \begin{cases} \alpha\theta(1-F(p_d+\xi)) & \text{if } p_d+\xi < \min(p_c+h_c, p_f+\mathbb{E}[\min(\Phi h_f, f+\xi)]) \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{D,CD} = \begin{cases} \alpha(1-\theta)(1-F(p_d+\xi)) & \text{if } p_d+\xi < \min(p_c+h_c+k, p_f+\mathbb{E}[\min(\Phi h_f, f+\xi)]) \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{D,UI} = \begin{cases} (1-\alpha)\theta(1-F(p_d)) & \text{if } p_d < \min(p_c+h_c, p_f+\mathbb{E}[\min(\Phi h_f, f)]) \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{D,UD} = \begin{cases} (1-\alpha)(1-\theta)(1-F(p_d)) & \text{if } p_d < \min(p_c+h_c+k, p_f+\mathbb{E}[\min(\Phi h_f, f)]) \\ 0 & \text{otherwise.} \end{cases}$$

Given $d_{D,CI}, d_{D,CD}, d_{D,UI}, d_{D,UD}$, the total demand for product with disposable packaging is still given by Equation (6).

$$d_{C,CI} = \begin{cases} \alpha\theta(1-F(p_c+h_c)) & \text{if } p_c+h_c \le \min(p_d+\xi, p_f+\mathbb{E}[\min(\Phi h_f, f+\xi)]) \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{C,CD} = \begin{cases} \alpha(1-\theta)(1-F(p_c+h_c+k)) & \text{if } p_c+h_c+k \le \min(p_d+\xi, p_f+\mathbb{E}[\min(\Phi h_f, f+\xi)]) \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{C,UI} = \begin{cases} (1-\alpha)\theta(1-F(p_c+h_c)) & \text{if } p_c+h_c \le \min(p_d, p_f+\mathbb{E}[\min(\Phi h_f, f)]) \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{C,UD} = \begin{cases} (1-\alpha)(1-\theta)(1-F(p_c+h_c+k)) & \text{if } p_c+h_c+k \le \min(p_d, p_f+\mathbb{E}[\min(\Phi h_f, f)]) \\ 0 & \text{otherwise.} \end{cases}$$

Given $d_{C,CI}, d_{C,CD}, d_{C,UI}, d_{C,UD}$, the total demand for product with consumer-owned reusable packaging is still given by Equation (7).

$$d_{F,CI} = \begin{cases} \alpha\theta(1-F(p_f+\mathbb{E}[\min(\Phi h_f, f+\xi)])) & \text{if } p_f+\mathbb{E}[\min(\Phi h_f, f+\xi)] \le \min(p_d+\xi, p_c+h_c) \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{F,CD} = \begin{cases} \alpha(1-\theta)(1-F(p_f + \mathbb{E}[\min(\Phi h_f, f+\xi)])) & \text{if } p_f + \mathbb{E}[\min(\Phi h_f, f+\xi)] \leq \min(p_d+\xi, p_c+h_c+k) \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{F,UI} = \begin{cases} (1-\alpha)\theta(1-F(p_f + \mathbb{E}[\min(\Phi h_f, f)])) & \text{if } p_f + \mathbb{E}[\min(\Phi h_f, f)] \leq \min(p_d, p_c+h_c) \\ 0 & \text{otherwise.} \end{cases}$$

$$d_{F,UD} = \begin{cases} (1-\alpha)(1-\theta)(1-F(p_f + \mathbb{E}[\min(\Phi h_f, f)])) & \text{if } p_f + \mathbb{E}[\min(\Phi h_f, f)] \leq \min(p_d, p_c+h_c+k) \\ 0 & \text{otherwise.} \end{cases}$$

Given $d_{F,CI}, d_{F,CD}, d_{F,UI}, d_{F,UD}$, the total demand for product with firm-owned reusable packaging is still given by Equation (17). Accordingly, the number of consumers who borrow a firm-owned reusable container and successfully return it after use is given by (18), while the number of consumers who borrow a firm-owned reusable container and fail to return it after use is given by Equation (19).

Comparing the demand functions with those in the main model (i.e., Equations (2)-(5) and (11)-(16)), we make the following observations. First, the presence of valuation heterogeneity does not affect consumers' choice between packaging types, nor their return decision if they select firm-owned reusable packaging. This is evident from the fact that the conditions for all the demand functions representing consumers' packaging and return choices are the same as those in the main model. This result is straightforward because the valuation term V (i) appears as the same constant in consumer utility functions regardless of packaging type and (ii) is irrelevant when it comes to the packaging return decision. Second, valuation heterogeneity plays a crucial role in consumers' purchase decisions, even within the same segment. Specifically, in the main model with homogeneous valuation, the firm faces only two discrete pricing options for each segment: it can either set a low price to cover the entire segment or a high price to exclude it entirely. In contrast, when consumer valuations are heterogeneous, the firm can fine-tune its pricing to target any fraction of each segment. This introduces a continuum of potential pricing strategies and results in smoother demand functions, as seen in the $(1 - F(\cdot))$ terms above. Consequently, the firm can set prices so that only consumers above a certain valuation threshold will purchase, allowing for more flexible and granular control over market coverage and profit optimization.

The goal of this extension is to check the robustness of our key results in the main model (Propositions 1 – 4). However, due to model complexity, we have to rely on a numerical approach to verify their robustness. Specifically, we consider the case where V is heterogeneous with distribution $F(V) = V/2v$ for $V \in [0, 2v]$. In this way, it has the same mean as in the main model. To ensure consistency with the analysis in the main model, we impose the same set of conditions: $c_d < h_c$ and $c_r(1) > c_d$, and thereby exclude scenarios that do not satisfy these assumptions.

We first check the robustness of the key insight of Proposition 1. To examine the impact of α on the introduction decision, we generate 100,000 scenarios for all model parameters (except for α) based on the distribution described at Section 6. In each scenario, given any fraction of eco-conscious consumers α, we compute the firm's optimal decisions $(p_d^b, p_c^b, p_d^f, p_c^f, p_f^f, f^f)$. We then conduct an exhaustive search over the grid $\alpha = 0.4 + 0.001(i-1)_{i=1}^{201} \triangleq \mathbb{G}_\alpha$ and evaluate the corresponding profit (π^b, π^f). We find that the scenario described in Proposition 1(ii) arises in 9.41% of cases. Specifically,

in these scenarios, there exist two values $\alpha_1 < \alpha_2$ in $\mathbb{G}_\alpha$ such that the firm introduces its reusable packaging at a low fraction of eco-conscious consumers but stops offering it at a higher fraction, i.e., $\pi^f|_{\alpha_1} > \pi^b|_{\alpha_1}$ and $\pi^f|_{\alpha_2} < \pi^b|_{\alpha_2}$.

Next, we quantify the impact of introducing firm-owned reusable packaging on packaging waste and verify the key insight of Proposition 2. Across the calibrated scenarios, the relative reduction in packaging waste, measured as $\frac{W^b - W^f}{W^b}$, has a median of approximately 14.5% and an interquartile range from 9.2% to 21.1%. These results indicate that firm-owned reusable packaging can deliver substantial and economically meaningful reductions in packaging waste. Nevertheless, waste reduction is not guaranteed. In particular, there exist scenarios in which the introduction of reusable packaging leads to an increase in average packaging waste per unit sold (i.e., $W^f > W^b$). We therefore compute the proportion of scenarios in which $W^f > W^b$ across four intervals of c_d: $[0.05, 0.075)$, $[0.075, 0.1)$, $[0.1, 0.125)$, and $[0.125, 0.15]$. The corresponding proportions are 8.9%, 11.2%, 14.1%, and 17.1%, respectively. These findings indicate that the key insight of Proposition 2 continues to hold: although firm-owned reusable packaging typically reduces waste, it may increase average packaging waste in a non-negligible subset of scenarios.

Next, we verify the results in Propositions 3 and 4. We begin by examining the impact of reducing h_c. Specifically, we regenerate 100,000 scenarios for all model parameters (except for h_c) based on the distributions described at Section 6. In each scenario, given any hassle cost h_c, we compute the firm's optimal decisions $(p_d^b, p_c^b, p_d^f, p_c^f, p_f^f, f^f)$. We thereafter conduct an exhaustive search and evaluate π^b, π^f, W^b and W^f over the following grid of h_c value $\{h_c = \max(c_d, 0.15) + 0.001(i-1)\}_{i=1}^{1+1000(0.4-\max(c_d,0.15))} \triangleq \mathbb{G}_c$. We exclude the scenario where $\pi^f < \pi^b$ for all $h_c \in \mathbb{G}_c$. In our analysis, we do not find any $h_{c1}, h_{c2} \in \mathbb{G}_c$ with $h_{c1} < h_{c2}$ such that $\pi^f(h_{c1}) < \pi^f(h_{c2})$ or $W^f(h_{c1}) > W^f(h_{c2})$. This finding is consistent with Propositions 3(i) and 4(i).

To examine the impact of reducing h_f, we adopt a similar approach. We regenerate 100,000 scenarios for all model parameters (except for h_f) based on the distributions described in Section 6. In each scenario, for any given hassle cost h_f, we compute the firm's optimal decisions: p_d^b, p_c^b, p_d^f, p_c^f, p_f^f, and f^f. We then conduct an exhaustive search and evaluate W^f over the following grid of h_f values: $\{h_f = 0.1 + 0.001(i-1)\}_{i=1}^{251} \triangleq \mathbb{G}_f$. After applying the model assumptions as before, we generate 100,000 scenarios. We do not find any $h_{f1}, h_{f2} \in \mathbb{G}_f$ with $h_{f1} < h_{f2}$ such that $\pi^f(h_{f1}) < \pi^f(h_{f2})$. This finding is consistent with Proposition 3(ii). We next compute the proportion of scenarios in which there exist $h_{f1} < h_{f2} \in \mathbb{G}_f$ such that $W^f(h_{f1}) > W^f(h_{f2})$ for each of the following three ranges of h_c: $[0.15, 0.25)$, $[0.25, 0.35)$, and $[0.35, 0.4]$. The corresponding proportions are 0.0%, 10.9%, and 33.6%, respectively. This pattern is consistent with the main analysis and shows that the key insight of Proposition 4(ii) still holds: there exists a pair of hassle costs $h_{f1} < h_{f2}$ such that the firm introduces its reusable packaging at both values, yet average packaging waste strictly increases as the hassle cost decreases (i.e., $\exists\ h_{f1} < h_{f2} \in \mathbb{G}_f$ such that $\min(\pi^f(h_{f1}), \pi^f(h_{f2})) > \pi^b$ and $W^f(h_{f1}) > W^f(h_{f2})$).

Online Supplement III Heterogeneous Environmental Disutility

In the main model, we assumed that eco-conscious consumers experience a homogeneous disutility ξ when generating packaging waste. In this subsection, we conduct a robustness check by relaxing this assumption. We assume that the disutility Ξ is heterogeneous across eco-conscious consumers

and follows a general distribution with a cumulative distribution function $G(\cdot)$. The main model corresponds to the special case where $\Xi = \xi$ with probability one. Consumers' utility functions remain structurally the same as in the main model, with ξ replaced by Ξ. Based on this setup, we derive the demand functions for two scenarios: the benchmark model (without firm-owned reusable packaging) and the main model (with firm-owned reusable packaging). Note that the utility function of eco-unconscious consumers remains the same as in the main body of the paper; therefore, the demand functions of type-UI and type-UD remain the same.

Online Supplement III.1 Model Without Firm-Owned Reusable Packaging

In this benchmark scenario, consumers decide whether to purchase the product and, if so, choose between disposable packaging and consumer-owned reusable packaging. Based on utility maximization, a type-CI consumer chooses disposable packaging if and only if $v - p_d - \Xi \geq \max(v - p_c - h_c, 0)$. Similarly, a type-CD consumer chooses disposable packaging if and only if $v - p_d - \Xi \geq \max(v - p_c - h_c - k, 0)$. These conditions imply that consumers select disposable packaging only when their environmental disutility Ξ is sufficiently low. Accordingly, we can define the following thresholds:

$$\xi_1 = v - p_d \tag{OS.III.1}$$

$$\xi_{2,CI} = h_c + p_c - p_d \tag{OS.III.2}$$

$$\xi_{2,CD} = h_c + p_c + k - p_d \tag{OS.III.3}$$

Then, for type-CI consumers, they will choose to purchase the product with disposable packaging if and only if $\Xi \leq \min(\xi_1, \xi_{2,CI})$. Therefore, the demand function is:

$$d_{D,CI} = \alpha\theta G(\min(\xi_1, \xi_{2,CI})) \tag{OS.III.4}$$

Similarly, for type-CD consumers, they will choose to purchase the product with disposable packaging if and only if $\Xi \leq \min(\xi_1, \xi_{2,CD})$. Therefore, the demand function is:

$$d_{D,CD} = \alpha(1-\theta) G(\min(\xi_1, \xi_{2,CD})) \tag{OS.III.5}$$

For type-CI consumers, they will choose to purchase the product with consumer-owned reusable packaging if and only if $\Xi \geq \xi_{2,CI}$ and $p_c \leq v - h_c$. Therefore, the demand function can be written as:

$$d_{C,CI} = \begin{cases} \alpha\theta(1 - G(\xi_{2,CI})) & \text{if } p_c \leq v - h_c, \\ 0 & \text{otherwise.} \end{cases} \tag{OS.III.6}$$

For type-CD consumers, they will choose to purchase the product with consumer-owned reusable packaging if and only if $\Xi \geq \xi_{2,CD}$ and $p_c \leq v - h_c - k$. Therefore, the demand function can be written as:

$$d_{C,CD} = \begin{cases} \alpha(1-\theta)(1 - G(\xi_{2,CD})) & \text{if } p_c \leq v - h_c - k, \\ 0 & \text{otherwise.} \end{cases} \tag{OS.III.7}$$

Online Supplement III.2 Model With Firm-Owned Reusable Packaging

In this model, consumers have four choices: (i) purchasing the product with disposable packaging; (ii) purchasing the product with consumer-owned reusable packaging; (iii) purchasing the product with firm-owned reusable packaging; and (iv) not purchasing. Consumers compare the utilities derived from these options and select the one that yields the highest utility.

We first compare the utility of using disposable packaging with that of using firm-owned reusable packaging. According to the utility functions, an eco-conscious consumer prefers disposable packaging to firm-owned reusable packaging only if $v-p_d-\Xi \geq v-p_f-[\beta\min(h_f, f+\Xi)+(1-\beta)\min(\phi h_f, f+\Xi)]$, which is equivalent to $\Xi-[\beta\min(h_f, f+\Xi)+(1-\beta)\min(\phi h_f, f+\Xi)] \leq p_f-p_d$. Note that the left-hand side of this inequality is (weakly) increasing in Ξ. Furthermore, we can find that the minimum value of $\Xi-[\beta\min(h_f, f+\Xi)+(1-\beta)\min(\phi h_f, f+\Xi)]$ is $-f$. Then, we can derive the threshold as:

$$\xi_3 = \begin{cases} -\infty & \text{if } f \leq p_d - p_f \\ \frac{p_f-p_d+\beta h_f+(1-\beta)f}{\beta} & \text{if } p_d - p_f < f \leq p_d - p_f + \beta(\phi h_f - h_f) \\ (p_f - p_d) + \beta h_f + (1-\beta)\phi h_f & \text{if } f > p_d - p_f + \beta(\phi h_f - h_f) \end{cases} \tag{OS.III.8}$$

Therefore, eco-conscious consumers will prefer disposable packaging to firm-owned reusable packaging if and only if $\Xi < \xi_3$.

Next, we examine the preference between firm-owned and consumer-owned reusable packaging. Type-CI (resp. type-CD) consumers prefer firm-owned reusable packaging to consumer-owned reusable packaging (or not purchasing) if and only if: $v - p_f - [\beta\min(h_f, f+\Xi) + (1-\beta)\min(\phi h_f, f+\Xi)] \geq \max(v-p_c-h_c, 0)$ (resp. $v-p_f-[\beta\min(h_f, f+\Xi)+(1-\beta)\min(\phi h_f, f+\Xi)] \geq \max(v-p_c-h_c-k, 0)$). To simplify the notation, let $\mathbb{E}[\Phi]h_f \equiv \beta h_f + (1-\beta)\phi h_f$ denote the expected hassle cost of returning the packaging.

$$\xi_{4,CI} = \begin{cases} +\infty & \text{if } p_f < \min(v, h_c+p_c) - \mathbb{E}[\Phi]h_f \\ \frac{\min(v,h_c+p_c)-p_f-\beta h_f}{1-\beta} - f & \text{if } \min(v, h_c+p_c) - \mathbb{E}[\Phi]h_f < p_f < \min(v, h_c+p_c) - h_f \\ \min(v, h_c+p_c) - p_f - f & \text{if } p_f > \min(v, h_c+p_c) - h_f \end{cases} \tag{OS.III.9}$$

$$\xi_{4,CD} = \begin{cases} +\infty & \text{if } p_f \leq \min(v, h_c+p_c+k) - \mathbb{E}[\Phi]h_f \\ \frac{\min(v,h_c+p_c+k)-p_f-\beta h_f}{1-\beta} - f & \text{if } \min(v, h_c+p_c+k) - \mathbb{E}[\Phi]h_f < p_f \leq \min(v, h_c+p_c+k) - h_f \\ \min(v, h_c+p_c+k) - p_f - f & \text{if } p_f > \min(v, h_c+p_c+k) - h_f \end{cases} \tag{OS.III.10}$$

Given these thresholds, we can derive the final demand for each type of packaging (disposable packaging, consumer-owned reusable packaging and firm-owned reusable packaging). First, a type-CI consumer will choose to purchase the product with disposable packaging if and only if $\Xi \leq \min(\xi_1, \xi_{2,CI}, \xi_3)$.

$$d_{D,CI} = \alpha\theta G(\min(\xi_1, \xi_{2,CI}, \xi_3)) \tag{OS.III.11}$$

Similarly, a type-CD consumer will choose to purchase the product with disposable packaging if and only if $\Xi \leq \min(\xi_1, \xi_{2,CD}, \xi_3)$.

$$d_{D,CD} = \alpha(1-\theta)G(\min(\xi_1, \xi_{2,CD}, \xi_3)) \tag{OS.III.12}$$

Second, a type-CI consumer will choose to purchase the product with consumer-owned reusable packaging if and only if $\Xi \geq \max(\xi_{2,CI}, \xi_{4,CI})$ and $p_c \leq v - h_c$. Then, the corresponding demand function is:

$$d_{C,CI} = \begin{cases} \alpha\theta(1 - G(\max(\xi_{2,CI}, \xi_{4,CI}))) & \text{if } p_c \leq v - h_c \\ 0 & \text{otherwise.} \end{cases} \tag{OS.III.13}$$

Similarly, a type-CD consumer will choose to purchase the product with consumer-owned reusable packaging if and only if $\Xi \geq \max(\xi_{2,CD}, \xi_{4,CD})$ and $p_c \leq v - h_c - k$. Then, the corresponding demand function is:

$$d_{C,CD} = \begin{cases} \alpha(1-\theta)(1 - G(\max(\xi_{2,CD}, \xi_{4,CD}))) & \text{if } p_c \leq v - h_c - k \\ 0 & \text{otherwise.} \end{cases} \tag{OS.III.14}$$

Finally, a type-CI consumer will choose to purchase the product with firm-owned reusable packaging if and only if $\xi_3 \leq \Xi \leq \xi_{4,CI}$. Then, the corresponding demand function is:

$$d_{F,CI} = \alpha\theta \max(0, G(\xi_{4,CI}) - G(\xi_3)) \tag{OS.III.15}$$

Similarly, a type-CD consumer will choose to purchase the product with firm-owned reusable packaging if and only if $\xi_3 \leq \Xi \leq \xi_{4,CD}$. Then, the corresponding demand is:

$$d_{F,CD} = \alpha(1-\theta) \max(0, G(\xi_{4,CD}) - G(\xi_3)) \tag{OS.III.16}$$

Note that if an eco-conscious consumer with disutility level Ξ decides to borrow a firm-owned reusable container, she will return it in the effortless state if and only if $\Xi > \xi_5$, where

$$\xi_5 = h_f - f \tag{OS.III.17}$$

Accordingly, she will return it in the effortful-return state if and only if $\Xi \geq \xi_6$, where

$$\xi_6 = \phi h_f - f \tag{OS.III.18}$$

Therefore, the return rate is given by:

$$\begin{aligned} \rho_c = \frac{1}{d_{F,CI} + d_{F,CD}} \Big\{ & \beta \Big[\alpha\theta \max(0, G(\xi_{4,CI}) - G(\max(\xi_3, \xi_5))) \\ & \quad + \alpha(1-\theta) \max(G(\xi_{4,CD}) - G(\max(\xi_3, \xi_5)), 0) \Big] \\ & + (1-\beta) \Big[\alpha\theta \max(0, G(\xi_{4,CI}) - G(\max(\xi_3, \xi_6))) \\ & \quad + \alpha(1-\theta) \max(G(\xi_{4,CD}) - G(\max(\xi_3, \xi_6)), 0) \Big] \Big\} \end{aligned} \tag{OS.III.19}$$

Online Supplement III.3 Numerical Study

Comparing the above demand functions with those in the main model (i.e., Equations (2)-(5) and (11)-(16)), we make the following observations. First, the presence of heterogeneity does not alter the fundamental conditions governing an individual consumer's packaging choice. This is evident from the fact that a consumer with a specific Ξ value still follows the same utility comparison rules as in the main model (i.e., the threshold shown in Equation (OS.III.1)-(OS.III.3),(OS.III.8)-(OS.III.10),(OS.III.17)-(OS.III.18)). Second, heterogeneity in ξ plays a crucial role in determining the aggregate packaging adoption, even within the same eco-conscious consumer segment. Specifically, in the main model with homogeneous Ξ, consumer segments (such as type-CI or type-CD) behave identically: the firm

effectively faces a binary choice to either set incentives that convert the entire segment to reuse or allow the entire segment to use disposable packaging. In contrast, when Ξ is heterogeneous, the firm can fine-tune its pricing to target any fraction of eco-conscious segment. This introduces a continuum of potential packaging waste levels. Consequently, this leads to intra-segment behavioral divergence: the firm can set prices so that only consumers above a certain disutility threshold will adopt reusable packaging, while the remainder of the same segment continues to use disposable packaging, allowing for more flexible and granular control over the trade-off between profit margins and packaging waste.

The goal of this extension is to check the robustness of our key results in the main model (Propositions 1 – 4). However, due to model complexity, we have to rely on a numerical approach to verify their robustness. Specifically, we focus on the case where Ξ is heterogeneous with distribution $G(\Xi) = \Xi/2\xi$ for $\Xi \in [0, 2\xi]$. This heterogeneous case has the same mean as the main model with homogeneous ξ. To ensure consistency with the analysis in the main model, we impose the same set of conditions: $c_d < \min(h_c, c_r(1))$, and thereby exclude scenarios that do not satisfy these assumptions.

We first check the robustness of the key insight of Proposition 1. To examine the impact of α on the introduction decision, we generate 100,000 scenarios for all model parameters (except for α) based on the distribution described at Section 6. In each scenario, given any fraction of eco-conscious consumers α, we compute the firm's optimal decisions $(p_d^b, p_c^b, p_d^f, p_c^f, p_f^f, f^f)$. We then conduct an exhaustive search over the grid $\alpha = 0.4 + 0.001(i-1)_{i=1}^{201} \triangleq \mathbb{G}_\alpha$ and evaluate the corresponding profit (π^b, π^f). We find that the scenario described in Proposition 1(ii) arises in 3.97% of cases. Specifically, in these scenarios, there exist two values $\alpha_1 < \alpha_2$ in $\mathbb{G}_\alpha$ such that the firm introduces its reusable packaging at a low fraction of eco-conscious consumers but stops offering it at a higher fraction, i.e., $\pi^f|_{\alpha_1} > \pi^b|_{\alpha_1}$ and $\pi^f|_{\alpha_2} < \pi^b|_{\alpha_2}$.

Next, we quantify the impact of introducing firm-owned reusable packaging on packaging waste and verify the key insight of Proposition 2. Across the calibrated scenarios, the relative reduction in packaging waste, measured as $\frac{W^b - W^f}{W^b}$, has a median of approximately 17.0% and an interquartile range from 12.7% to 22.3%. These results indicate that firm-owned reusable packaging can deliver substantial and economically meaningful reductions in packaging waste. Nevertheless, waste reduction is not guaranteed. In particular, there exist scenarios in which the introduction of reusable packaging leads to an increase in average packaging waste per unit sold (i.e., $W^f > W^b$). We therefore compute the proportion of scenarios in which $W^f > W^b$ across four intervals of c_d: $[0.05, 0.075)$, $[0.075, 0.1)$, $[0.1, 0.125)$, and $[0.125, 0.15]$. The corresponding proportions are 4.9%, 6.3%, 8.1%, and 10.1%, respectively. These findings indicate that the key insight of Proposition 2 continues to hold: although firm-owned reusable packaging typically reduces waste, it may increase average packaging waste in a non-negligible subset of scenarios.

Next, we verify the results in Propositions 3 and 4. We begin by examining the impact of reducing h_c. Specifically, we regenerate 100,000 scenarios for all model parameters (except for h_c) based on the distributions described at Section 6. In each scenario, given any hassle cost h_c, we compute the firm's optimal decisions $(p_d^b, p_c^b, p_d^f, p_c^f, p_f^f, f^f)$. We thereafter conduct an exhaustive search and evaluate π^b, π^f, W^b and W^f over the following grid of h_c value $\{h_c = \max(c_d, 0.15) + 0.001(i-1)\}_{i=1}^{1+1000(0.4-\max(c_d,0.15))} \triangleq \mathbb{G}_c$. We exclude the scenario where $\pi^f < \pi^b$ for all $h_c \in \mathbb{G}_c$. In our analysis, we do not find any $h_{c1}, h_{c2} \in \mathbb{G}_c$ with $h_{c1} < h_{c2}$ such that $\pi^f(h_{c1}) < \pi^f(h_{c2})$ or

$W^f(h_{c1}) > W^f(h_{c2})$. This finding is consistent with Propositions 3(i) and 4(i).

To examine the impact of reducing h_f, we adopt a similar approach. We regenerate 100,000 scenarios for all model parameters (except for h_f) based on the distributions described at Section 6. In each scenario, for any given hassle cost h_f, we compute the firm's optimal decisions: p_d^b, p_c^b, p_d^f, p_c^f, p_f^f, and f^f. We then conduct an exhaustive search and evaluate W^f over the following grid of h_f values: $\{h_f = 0.1+0.001(i-1)\}_{i=1}^{251} \triangleq \mathbb{G}_f$. After applying the model assumptions as before, we generate 100,000 scenarios. We do not find any $h_{f1}, h_{f2} \in \mathbb{G}_f$ with $h_{f1} < h_{f2}$ such that $\pi^f(h_{f1}) < \pi^f(h_{f2})$. This finding is consistent with Proposition 3(ii). We next compute the proportion of scenarios in which there exist $h_{f1} < h_{f2} \in \mathbb{G}_f$ such that $W^f(h_{f1}) > W^f(h_{f2})$ for each of the following three ranges of h_c: $[0.15, 0.25)$, $[0.25, 0.35)$, and $[0.35, 0.4]$. The corresponding proportions are 9.2%, 13.5%, and 21.4%, respectively. This pattern is consistent with the main analysis and shows that the key insight of Proposition 4(ii) remains robust: there exists a pair of hassle costs $h_{f1} < h_{f2}$ such that the firm introduces its reusable packaging at both values, yet average packaging waste strictly increases as the hassle cost decreases (i.e., $\exists\ h_{f1} < h_{f2} \in \mathbb{G}_f$ such that $\min(\pi^f(h_{f1}), \pi^f(h_{f2})) > \pi^b$ and $W^f(h_{f1}) > W^f(h_{f2})$).

Online Supplement IV Additional Proofs

Proof of Lemma OA.I.1: Similar to the analysis in the proof of Lemma 2, there are five options for the firm's optimal strategy:

(0) Sell to all consumers and do not induce any consumers to use personal reusable packaging. Then, the firm sets $p_d = v - \xi$, $p_c = v - \xi$. The corresponding profit is:

$$\pi_0 = v - \xi - c_d$$

Note that this case can be feasible only if $\xi < h_c$.

(1) Sell to all consumers and induce type-CI consumers to use reusable packaging. Then, the firm sets $p_d = v - \xi$, $p_c = v - \max(h_c, \xi)$. The corresponding profit is

$$\pi_1 = \alpha\theta(v - \max(h_c, \xi)) + (1 - \alpha\theta)(v - \xi - c_d)$$

Note that this case can be feasible only if $\xi < h_c + k$.

(2) Sell to all consumers and induce type-CI, type-CD consumers to use reusable packaging. Then, the optimization problem is:

$$\begin{aligned} \max_{p_c, p_d}\ & \alpha p_c + (1-\alpha)(p_d - c_d) \\ s.t.\ & p_c \le v - h_c - k \\ & p_c + h_c + k - \xi \le p_d \le p_c + h_c + a \\ & p_d \le v \end{aligned}$$

Then, the firm sets $p_d = \min(v - k + a, v)$, $p_c = v - k - h_c$. The corresponding profit is:

$$\pi_2 = \alpha(v - k - h_c) + (1 - \alpha)(\min(v - k + a, v) - c_d).$$

Note that this case can hold only if $k < \xi + a$.

(3) Sell to type-CI, type-UI, and type-UD consumers and induce only type-CI consumers to use reusable packaging. Then, the firm should set $p_d = v$ and $p_c = v - h_c$. The corresponding profit

is:

$$\pi_3 = \alpha\theta(v - h_c) + (1 - \alpha)(v - c_d)$$

(4) Sell to all consumers and induce type-CI, type-CD, type-UI consumers to use reusable packaging.

Then, the optimization problem is:

$$\begin{aligned} \max_{p_c, p_d} \ & (\alpha + (1-\alpha)\theta)p_c + (1-\alpha)(1-\theta)(p_d - c_d) \\ s.t. \ & p_c \le v - h_c - k \\ & p_c \le v - h_c - a \\ & \max(p_c + h_c + k - \xi, p_c + h_c + a) \le p_d \le v \end{aligned}$$

Then, the firm should set $p_d = v$, $p_c = v - h_c - \max(k, a)$. The corresponding profit is:

$$\pi_4 = (\alpha + (1-\alpha)\theta)(v - h_c - \max(k, a)) + (1-\alpha)(1-\theta)(v - c_d)$$

Based on the above discussion, regardless of the value of a, we can find that strategies (0), (1) and (3) are the same as those in the proof of Lemma 2.

If $k > a$, strategy (4) remains the same. For strategy (2), the price p_d increases from $v - k$ to $v - k + a$. Now, we can find that $\pi_2 > \pi_3$ if and only if $k < \alpha(1-\theta)(v - h_c) + (1-\alpha)a$

Then, we define:

$$\bar{\mathcal{K}}^b = \min(\alpha(1-\theta)(v - h_c) + (1-\alpha)a, \xi + a)$$

We define the critical cost thresholds as follows:

$$\begin{aligned} C_{1,1} &= \inf\{c_d \ge 0 \mid \max(\pi_2, \pi_4) \ge \max(\pi_0, \pi_1)\}, \\ C_{1,2} &= \inf\{c_d \ge 0 \mid \max(\pi_3, \pi_4) \ge \max(\pi_0, \pi_1)\}, \\ C_{2,1} &= \inf\{c_d \ge 0 \mid \pi_4 \ge \max(\pi_0, \pi_1, \pi_2)\}, \\ C_{2,2} &= \inf\{c_d \ge 0 \mid \pi_4 \ge \max(\pi_0, \pi_1, \pi_3)\}. \end{aligned}$$

Then, we obtain the unified thresholds:

$$\bar{\mathcal{C}}_1^b = \begin{cases} C_{1,1} & \text{if } k < \bar{\mathcal{K}}^b, \\ C_{1,2} & \text{if } k \ge \bar{\mathcal{K}}^b, \end{cases} \quad \text{and} \quad \bar{\mathcal{C}}_2^b = \begin{cases} C_{2,1} & \text{if } k < \bar{\mathcal{K}}^b, \\ C_{2,2} & \text{if } k \ge \bar{\mathcal{K}}^b. \end{cases}$$

Then, we can arrive at the first part of Lemma OA.I.1.

If $k \le a$, then $\pi_4 < \pi_2$ always holds. We need to compare $\pi_0, \pi_1, \pi_2, \pi_3$. Note that $\pi_3 > \pi_2$ if and only if $k > (1-\theta)(v - h_c)$

Then, we define

$$\mathcal{C}_3^b = \begin{cases} \inf\{c_d \ge 0 \mid \pi_2 \ge \max(\pi_0, \pi_1)\} & \text{if } k \le (1-\theta)(v - h_c), \\ \inf\{c_d \ge 0 \mid \pi_3 \ge \max(\pi_0, \pi_1)\} & \text{if } k > (1-\theta)(v - h_c), \end{cases}$$

We know that:

- If $c_d \le \min((h_c - \xi)^+, \mathcal{C}_3^b)$, then the firm chooses strategy (0).
- If $(h_c - \xi)^+ < c_d \le \mathcal{C}_3^b$, then the firm chooses strategy (1).
- If $c_d > \mathcal{C}_3^b$ and $k \le (1-\theta)(v - h_c)$, the firm chooses strategy (2).
- If $c_d > \mathcal{C}_3^b$ and $k > (1-\theta)(v - h_c)$, the firm chooses strategy (3).

To sum up the above discussion, we can arrive at the second part of Lemma OA.I.1. □

Proof of Lemma OA.II.1: In the benchmark model without firm-owned reusable packaging, the presence of e_d does not change any equilibrium outcomes (i.e.,Lemma 2), where we just need to replace ξ with ξ_d. Then, we arrive at Lemma OA.II.1. □

Proof of Lemma OA.II.2: In the model with firm-owned reusable packaging, to ensure some consumers to use firm-owned reusable packaging, we must have $v-p_f-\mathbb{E}[\min(\Phi h_f, f+\xi_r)] \geq v-\xi_d-p_d$. Then, in the equilibrium outcome, all eco-conscious consumers will choose between personal reusable packaging and firm-owned reusable packaging. In other words, no eco-conscious consumer chooses disposable packaging and ξ_d does not appear in the equilibrium outcome. Therefore, the equilibrium outcome remains the same with our main model (i.e.,Lemma 3), and we just need to replace ξ with ξ_r. □

Proof of Proposition OA.II.1: Because π^f is strictly decreasing in $c_{r,o}$ whereas π^b is independent of $c_{r,o}$, part (i) follows from the proof of Proposition 1(i).

For part (ii), we focus on $\xi_d > (1-\beta)\xi_r$. If this condition fails, firm-owned reusable packaging with a return rate of $\beta < 1$ imposes weakly greater expected environmental disutility and has a strictly higher unit cost than disposable packaging because $c_r(\beta) > c_d$. Thus, the firm has no incentive to offer such an imperfect-return program.

When $c_d < \tilde{\mathcal{C}}_1^b$,

$$\pi^b = v - \xi_d - c_d + \alpha\theta \max(0, \xi_d + c_d - \max(\xi_d, h_c)).$$

As in the proof of Proposition 1(ii), write

$$\pi_k = g_{1,k} - \alpha g_{2,k}(c_{r,o}), \qquad k \in \{a,b,c,d\},$$

where $g_{2,k}(c_{r,o})$ is strictly increasing in $c_{r,o}$. Moreover,

$$g_{1,k} - (v - \xi_d - c_d) = \begin{cases} \xi_d - (1-\beta)\xi_r, & k \in \{a,c\}, \\ \xi_d, & k \in \{b,d\}, \end{cases} > 0.$$

Therefore, the proof of Proposition 1(ii) applies directly, yielding

$$\pi^f > \pi^b \iff c_{r,o} < \max_{k\in\{a,b,c,d\}} \tilde{\mathcal{C}}_k^f(\alpha),$$
$$\tilde{\mathcal{C}}^f(\alpha) = \max_{k\in\{a,b,c,d\}} \tilde{\mathcal{C}}_k^f(\alpha),$$

where $\tilde{\mathcal{C}}^f(\alpha)$ is strictly decreasing in α. Hence, choosing $\alpha_1 < \alpha_2$ and

$$\tilde{\mathcal{C}}^f|_{\alpha=\alpha_2} < c_{r,o} < \tilde{\mathcal{C}}^f|_{\alpha=\alpha_1}$$

yields the result in part (ii). □

Proof of Proposition OA.II.2: Similar to the proof of Proposition 2, we know $E^b = (1-\alpha)(1-\theta)e_d$ when $c_d > \tilde{\mathcal{C}}_2^b$. Furthermore, we know $E^f \geq (1-\alpha)e_d$. Therefore, $E^b < E^f$ when $c_d > \tilde{\mathcal{C}}_2^b$. □

Proof of Proposition OA.II.3: From Lemma OA.II.2, the equilibrium outcome under hetero-

geneous environmental impact is functionally identical to that derived in Lemma 3, subject to the parameter substitution of ξ_r for ξ. Therefore, we still conclude that π^f is decreasing in both h_c and h_f. □

Proof of Proposition OA.II.4: Based on Lemma OA.II.2, the average environmental impacts under the four candidate strategies are given by:

- $E^f(a) = (1-\alpha)e_d + \alpha(1-\theta)(1-\beta)e_r$
- $E^f(b) = (1-\alpha)e_d$
- $E^f(c) = (1-\alpha)e_d + \alpha(1-\beta)e_r$
- $E^f(d) = (1-\alpha)e_d$

Evidently, the term $(1-\alpha)e_d$ is common across all strategies; thus, e_d does not influence the ordinal comparison of the strategies' environmental impacts. The relative differences are governed solely by e_r. Given the identical equilibrium structure in Lemma OA.II.2 and Lemma 3, the impact of h_c and h_f on E^f can be established in the same way as in the proof of Proposition 4.

Following the logic established in the proof of Proposition 4, it follows that E^f remains monotonically increasing in h_c. Furthermore, there exists a threshold $\tilde{\mathcal{H}}^*$ such that as the firm's cost h_f decreases from h_{f2} to h_{f1}, the firm's optimal strategy shifts from (a) to (c) when $h_c > \tilde{\mathcal{H}}^*$. Under this transition, the average environmental impact E^f increases from $(1-\alpha)e_d + \alpha(1-\theta)(1-\beta)e_r$ to $(1-\alpha)e_d + \alpha(1-\beta)e_r$. □

Proof of Lemma OS.I.1: Recall that the conditions for consumers to prefer personal reusable packaging to disposable packaging are given by:

- For type-CI consumers: $p_d - p_c \geq \frac{h_c-\xi}{\gamma}$.
- For type-CD consumers: $p_d - p_c \geq \frac{h_c+k-\xi}{\gamma}$.
- For type-UI consumers: $p_d - p_c > h_c$.
- For type-UD consumers: $p_d - p_c > h_c + k$.

If $\gamma < \frac{h_c-\xi}{h_c+k}$, then the firm has no economic motivation to offer a discount large enough to incentivize consumers to adopt personal reusable packaging. Thus, we assume $\gamma \geq \frac{h_c-\xi}{h_c+k}$, or equivalently, $\xi \geq h_c - \gamma(h_c+k)$.

The optimal strategy is chosen from the following options:

(b.0) Sell to all consumers and do not induce any consumers to use personal reusable packaging. Then, $p_d = p_c = v - \xi$. The corresponding profit is $\pi_0 = v - \xi - c_d$. Note that this strategy is feasible if and only if $\xi < h_c$.

(b.1) Sell to all consumers and induce only type-CI consumers to use personal reusable packaging. Then, $p_d = v - \xi$ and $p_c = v - \xi - \frac{(h_c-\xi)^+}{\gamma}$. The corresponding profit is $\pi_1 = \alpha\theta(v - \xi - \frac{(h_c-\xi)^+}{\gamma}) + (1-\alpha\theta)(v-\xi-c_d)$. Note that this case is feasible when $(1-\gamma)h_c < \xi < h_c + k$.

(b.2) Sell to only eco-unconscious consumers. Then, $p_d = p_c = v$. The corresponding profit is $\pi_2 = (1-\alpha)(v-c_d)$.

(b.3) Sell to type-CI consumers and all eco-unconscious consumers, and induce only type-CI con-

sumers to use personal reusable packaging. The profit maximization problem is:

$$\begin{aligned}\max_{p_d,p_c} \quad & \pi = \alpha\theta p_c + (1-\alpha)(p_d - c_d) \\ s.t. \quad & v - h_c - p_d + \gamma(p_d - p_c) \geq 0 \\ & p_d \leq \min(p_c + h_c, v) \\ & v - \xi - p_d \leq 0 \\ & v - h_c - k - p_d + \gamma(p_d - p_c) \leq 0\end{aligned}$$

Note that this case is feasible when $\xi > (1-\gamma)h_c$.

- If $\gamma > \frac{\alpha\theta}{\alpha\theta+1-\alpha}$, then $p_d = v - h_c + \gamma h_c$, $p_c = v - h_c + (\gamma-1)h_c$. The corresponding profit is $\pi_3 = \alpha\theta(v - h_c + (\gamma-1)h_c) + (1-\alpha)(v - h_c + \gamma h_c - c_d)$.
- If $\gamma \leq \frac{\alpha\theta}{\alpha\theta+1-\alpha}$, then $p_d = v - h_c + (h_c - \xi)^+$, $p_c = v - h_c + (h_c - \xi)^+ - \frac{(h_c-\xi)^+}{\gamma}$. The corresponding profit is $\pi_3 = \alpha\theta(v - h_c + (h_c-\xi)^+ - \frac{(h_c-\xi)^+}{\gamma}) + (1-\alpha)(v - h_c + (h_c-\xi)^+ - c_d)$.

To sum up, the optimal prices for this case are $p_d = v - h_c + \gamma(h_c I_{\gamma > \frac{\alpha\theta}{\alpha\theta+1-\alpha}} + \frac{(h_c-\xi)^+}{\gamma} I_{\gamma \leq \frac{\alpha\theta}{\alpha\theta+1-\alpha}})$ and $p_c = v - h_c + (\gamma-1)(h_c I_{\gamma > \frac{\alpha\theta}{\alpha\theta+1-\alpha}} + \frac{(h_c-\xi)^+}{\gamma} I_{\gamma \leq \frac{\alpha\theta}{\alpha\theta+1-\alpha}})$.

(b.4) Sell to all consumers and induce type-CI and type-CD consumers to use personal reusable packaging.

$$\begin{aligned}\max_{p_d,p_c} \quad & \pi = \alpha p_c + (1-\alpha)(p_d - c_d) \\ s.t. \quad & v - k - h_c - p_d + \gamma(p_d - p_c) \geq 0 \\ & v - p_d \geq 0 \\ & p_d - p_c \leq h_c \\ & \gamma(p_d - p_c) \geq h_c + k - \xi\end{aligned}$$

Note that this case is feasible if and only if $\xi > (1-\gamma)h_c + k$.

- If $\gamma > \alpha$, then $p_d = v - k - h_c + \gamma h_c$, $p_c = v - k - h_c + (\gamma-1)h_c$. The corresponding profit is $\pi_4 = \alpha(v - k - h_c + (\gamma-1)h_c) + (1-\alpha)(v - k - h_c + \gamma h_c - c_d)$.
- If $\gamma \leq \alpha$, then $p_d = v - k - h_c + (h_c + k - \xi)^+$, $p_c = v - k - h_c + (\gamma-1)\frac{(h_c+k-\xi)^+}{\gamma}$. The corresponding profit is $\pi_4 = \alpha(v - k - h_c + (\gamma-1)\frac{(h_c+k-\xi)^+}{\gamma}) + (1-\alpha)(v - k - h_c + (h_c + k - \xi)^+ - c_d)$.

The optimal prices for this case are $p_d = v - k - h_c + \gamma(h_c I_{\gamma>\alpha} + \frac{(h_c+k-\xi)^+}{\gamma} I_{\gamma \leq \alpha})$ and $p_c = v - k - h_c + (\gamma-1)(h_c I_{\gamma>\alpha} + \frac{(h_c+k-\xi)^+}{\gamma} I_{\gamma \leq \alpha})$.

(b.5) Sell to type-CI consumers and all eco-unconscious consumers, and induce type-CI and type-UI consumers to use personal reusable packaging.

$$\begin{aligned}\max_{p_d,p_c} \quad & \pi = \theta p_c + (1-\alpha)(1-\theta)(p_d - c_d) \\ s.t. \quad & v - h_c - p_d + \gamma(p_d - p_c) \geq 0 \\ & p_d \geq p_c + h_c \\ & p_d \leq \min(v, p_c + h_c + k) \\ & v - \xi - p_d \leq 0 \\ & v - h_c - k - p_d + \gamma(p_d - p_c) \leq 0\end{aligned}$$

- If $\gamma > \frac{\theta}{\alpha\theta+1-\alpha}$, then $p_d = v - h_c + \gamma \min(\frac{h_c}{\gamma}, h_c + k)$, $p_c = v - h_c + (\gamma-1)\min(\frac{h_c}{\gamma}, h_c + k)$.

The corresponding profit is $\pi_5 = \theta(v - h_c + (\gamma-1)\min(\frac{h_c}{\gamma}, h_c + k)) + (1-\alpha)(1-\theta)(v - h_c + \gamma\min(\frac{h_c}{\gamma}, h_c + k) - c_d)$.

– If $\gamma < \frac{\theta}{\alpha\theta+1-\alpha}$, then $p_d = v - h_c + \gamma\max(h_c, \frac{h_c-\xi}{\gamma})$, $p_c = v - h_c + (\gamma-1)\max(h_c, \frac{h_c-\xi}{\gamma})$. The corresponding profit is $\pi_5 = \theta(v - h_c + (\gamma-1)\max(h_c, \frac{h_c-\xi}{\gamma})) + (1-\alpha)(1-\theta)(v - h_c + \gamma\max(h_c, \frac{h_c-\xi}{\gamma}) - c_d)$.

To sum up, the optimal prices for this case are $p_d = v - h_c + \gamma(\min(\frac{h_c}{\gamma}, h_c + k)I_{\gamma > \frac{\theta}{\alpha\theta+1-\alpha}} + \max(h_c, \frac{h_c-\xi}{\gamma})I_{\gamma \le \frac{\theta}{\alpha\theta+1-\alpha}})$ and $p_c = v - h_c + (\gamma-1)(\min(\frac{h_c}{\gamma}, h_c + k)I_{\gamma > \frac{\theta}{\alpha\theta+1-\alpha}} + \max(h_c, \frac{h_c-\xi}{\gamma})I_{\gamma \le \frac{\theta}{\alpha\theta+1-\alpha}})$.

(b.6) Sell to all consumers and induce type-CI, type-CD, and type-UI consumers to use personal reusable packaging.

$$\begin{aligned} \max_{p_d, p_c} \quad & \pi = (\alpha + (1-\alpha)\theta)p_c + (1-\alpha)(1-\theta)(p_d - c_d) \\ s.t. \quad & v - k - h_c - p_d + \gamma(p_d - p_c) \ge 0 \\ & v - p_d \ge 0 \\ & p_d - p_c \le h_c + k \\ & p_d - p_c \ge h_c \\ & \gamma(p_d - p_c) \ge h_c + k - \xi \end{aligned}$$

Note that this case is feasible when $\gamma > \frac{h_c+k-\xi}{h_c+k}$, or equivalently, $\xi > (1-\gamma)(h_c + k)$.

– If $\gamma > \alpha + (1-\alpha)\theta$, then $p_d = v - k - h_c + \gamma(h_c + k)$, $p_c = v - k - h_c + (\gamma-1)(h_c + k)$. The corresponding profit is $\pi_6 = (\alpha + (1-\alpha)\theta)(v - k - h_c + (\gamma-1)(h_c + k)) + (1-\alpha)(1-\theta)(v - k - h_c + \gamma(h_c + k) - c_d)$.

– If $\gamma < \alpha + (1-\alpha)\theta$, then $p_d = v - k - h_c + \gamma\max(h_c, \frac{k+h_c-\xi}{\gamma})$, $p_c = p_d - \max(h_c, \frac{h_c+k-\xi}{\gamma})$. The corresponding profit is $\pi_6 = (\alpha + (1-\alpha)\theta)(v - k - h_c + (\gamma-1)\max(h_c, \frac{h_c+k-\xi}{\gamma})) + (1-\alpha)(1-\theta)(v - k - h_c + \gamma\max(h_c, \frac{h_c+k-\xi}{\gamma}) - c_d)$.

To sum up, the optimal prices for this case are $p_d = v - h_c - k + \gamma[(h_c + k)I_{\gamma > \alpha+(1-\alpha)\theta} + \max(h_c, \frac{h_c+k-\xi}{\gamma})I_{\gamma \le \alpha+(1-\alpha)\theta}]$.

Summarizing the above results, we arrive at Lemma OS.I.1. □

Proof of Lemma OS.I.2: Similar to Lemma 3, in equilibrium, type-CD consumers must adopt firm-owned reusable packaging, and type-UD consumers must adopt disposable packaging. However, due to the crowding-out effect, type-UI consumers might now be incentivized to use consumer-owned reusable packaging. In all cases discussed below, the participation constraint for type-CD consumers, $v - \mathbb{E}[\min(\Phi h_f, f + \xi)] - p_d + \gamma(p_d - p_f) \ge 0$, is always binding to maximize the firm's profit from firm-owned packaging. Thus, we always have:

$$p_f(p_d) = \frac{1}{\gamma}(v - \mathbb{E}[\min(\Phi h_f, f + \xi)] - (1-\gamma)p_d)$$

The optimal strategy is chosen from three cases:

(f.1) Sell to all consumers, and induce type-CI consumers to use personal reusable packaging and

type-CD consumers to use firm-owned reusable packaging. The optimization problem is:

$$\begin{aligned}\max_{p_d,p_c,p_f,f}\ & \alpha\theta p_c+\alpha(1-\theta)(p_f+f\mathbb{E}[I_{\Phi h_f>f+\xi}]-c_r(\rho(f)))+(1-\alpha)(p_d-c_d)\\ s.t.\ & \frac{\mathbb{E}[\min(\Phi h_f,f+\xi)]-\xi}{\gamma}\le p_d-p_f\le\mathbb{E}[\min(\Phi h_f,f)]\\ & p_d-p_f+\frac{h_c-\mathbb{E}[\min(\Phi h_f,f+\xi)]}{\gamma}\le p_d-p_c\\ & p_d-p_c\le\min(h_c,p_d-p_f+\frac{h_c+k-\mathbb{E}[\min(\Phi h_f,f+\xi)]}{\gamma})\end{aligned}$$

According to the above constraints, we can find that we need to ensure $\min(\mathbb{E}[\min(\Phi h_f,f)],h_c-\frac{h_c-\mathbb{E}[\min(\Phi h_f,f+\xi)]}{\gamma})>(\frac{\mathbb{E}[\min(\Phi h_f,f+\xi)]-\xi}{\gamma})^+$. Otherwise, the above case is not feasible. A sufficient condition such that the above case is not feasible is that $h_c>\frac{\max(\mathbb{E}[\Phi]h_f,\xi)}{1-\gamma}$.

Then, based on the above optimization problem, we find that $p_{f1}=\frac{1}{\gamma}(v-\mathbb{E}[\min(\Phi h_f,f+\xi)]-(1-\gamma)p_d)$, $p_{c1}=\min(p_{d1},p_{f1}-\frac{h_c-\mathbb{E}[\min(\Phi h_f,f+\xi)]}{\gamma})$. Furthermore,

- If $\gamma>\alpha$, then $p_{d1}=v-\mathbb{E}[\min(\Phi h_f,f+\xi)]+\gamma\min\Big(\mathbb{E}[\min(\Phi h_f,f)],h_c-\frac{h_c-\mathbb{E}[\min(\Phi h_f,f+\xi)]}{\gamma}\Big)$.
- If $\alpha(1-\theta)<\gamma\le\alpha$, then $p_{d1}=v-\mathbb{E}[\min(\Phi h_f,f+\xi)]+\gamma\max((\frac{\mathbb{E}[\min(\Phi h_f,f+\xi)]-\xi}{\gamma})^+,\min\Big(\frac{\mathbb{E}[\min(\Phi h_f,f+\xi)]-h_c}{\gamma},\mathbb{E}[\min(\Phi h_f,f)]\Big))$
- If $\gamma<\alpha(1-\theta)$, then $p_{d1}=v-\mathbb{E}[\min(\Phi h_f,f+\xi)]+\gamma(\frac{\mathbb{E}[\min(\Phi h_f,f+\xi)]-\xi}{\gamma})^+$.

Let $\pi_1(f|p_{d1},p_{c1},p_{f1})$ denote the corresponding profit function. Then, we need to find the optimal deposit f. Note that the profit function is always a piecewise linear function of f. There are two cases: (i) the firm sets a deposit $f>\phi h_f-\xi$, then the local optimal deposit is $f=\phi h_f$, since f does not affect the profit structure but a larger f can increase the upper bound of the constraint. (ii) the firm sets a deposit $f<\phi h_f-\xi$. Then, let f_1 be the local maximizer for the second case:

$$\begin{aligned}f_1=\arg\max_f\quad & \alpha\theta p_{c1}+\alpha(1-\theta)[p_{f1}+(1-\beta)f-c_r(\beta)]+(1-\alpha)(p_{d1}-c_d)\\ \text{s.t.}\quad & \max(0,h_f-\xi)\le f\le\phi h_f-\xi,\\ & \mathbb{E}[\min(\Phi h_f,f+\xi)]-\gamma\mathbb{E}[\min(\Phi h_f,f)]<\xi.\end{aligned}$$

Therefore, there are two possible optimal solutions for the deposit:

(f.1.1) $f=f_1<\phi h_f-\xi$, then consumers only return the firm-owned reusable packaging when they are in the effortless-return state.

(f.1.2) $f=\phi h_f$, then consumers always return the packaging.

(f.2) Sell to all consumers, and induce type-CI, type-UI consumers to use personal reusable packaging, and type-CD consumers to use firm-owned reusable packaging. The optimization problem is:

$$\begin{aligned}\max_{p_d,p_c,p_f,f}\ & \theta p_c+\alpha(1-\theta)(p_f+f\mathbb{E}[I_{\Phi h_f>f+\xi}]-c_r(\rho(f)))+(1-\alpha)(1-\theta)(p_d-c_d)\\ s.t.\ & \frac{\mathbb{E}[\min(\Phi h_f,f+\xi)]-\xi}{\gamma}\le p_d-p_f\le\mathbb{E}[\min(\Phi h_f,f)]\\ & \max(h_c,p_d-p_f+\frac{h_c-\mathbb{E}[\min(\Phi h_f,f+\xi)]}{\gamma})\le p_d-p_c\\ & p_d-p_c\le\min(h_c+k,p_d-p_f+\frac{h_c+k-\mathbb{E}[\min(\Phi h_f,f+\xi)]}{\gamma})\end{aligned}$$

Then, let (p_{d2}, p_{c2}, p_{f2}) be the optimal solution conditional on f in this case. Then, based on the above optimization problem, we find that $p_{c2} = \min(p_{d2} - h_c, p_{f2} - \frac{h_c - \mathbb{E}[\min(\Phi h_f, f+\xi)]}{\gamma})$, $p_{f2} = \frac{1}{\gamma}(v - \mathbb{E}[\min(\Phi h_f, f+\xi)] - (1-\gamma)p_{d2})$. Furthermore,

- If $\gamma > \alpha + (1-\alpha)\theta$, then $p_{d2} = v - \mathbb{E}[\min(\Phi h_f, f+\xi)] + \gamma\mathbb{E}[\min(\Phi h_f, f)]$.
- If $\alpha(1-\theta) < \gamma \leq \alpha + (1-\alpha)\theta$, then $p_{d2} = v - \mathbb{E}[\min(\Phi h_f, f+\xi)] + \gamma \max((\frac{\mathbb{E}[\min(\Phi h_f, f+\xi)] - \xi}{\gamma})^+, \min(\mathbb{E}[\min(\Phi h_f, f)], h_c - \frac{h_c - \mathbb{E}[\min(\Phi h_f, f+\xi)]}{\gamma}))$.
- If $\gamma < \alpha(1-\theta)$, then $p_{d2} = v - \mathbb{E}[\min(\Phi h_f, f+\xi)] + \gamma(\frac{\mathbb{E}[\min(\Phi h_f, f+\xi)] - \xi}{\gamma})^+$

Again, there are two options for the optimal deposit:

(f.2.1) $f = f_2$, where f_2 is the local maximizer for the case $f \leq \phi h_f - \xi$:

$$\begin{aligned} f_2 = \arg\max_f \quad & \theta p_{c2} + \alpha(1-\theta)[p_{f2} + (1-\beta)f - c_r(\beta)] + (1-\alpha)(1-\theta)(p_{d2} - c_d) \\ \text{s.t.} \quad & \max(0, h_f - \xi) \leq f \leq \phi h_f - \xi, \\ & \mathbb{E}[\min(\Phi h_f, f+\xi)] - \gamma\mathbb{E}[\min(\Phi h_f, f)] < \xi. \end{aligned}$$

Then, consumers only return the firm-owned reusable packaging when they are in the effortless-return state.

(f.2.2) $f = \phi h_f$, then consumers always return the packaging.

(f.3) Sell to all consumers, and induce all eco-conscious consumers to use firm-owned reusable packaging, and no consumer uses personal reusable packaging. The optimization problem is

$$\begin{aligned} \max_{p_d, p_c, p_f, f} \quad & \alpha(p_f + f\mathbb{E}[I_{\Phi h_f > f+\xi}] - c_r(\rho(f))) + (1-\alpha)(p_d - c_d) \\ s.t. \quad & \frac{\mathbb{E}[\min(\Phi h_f, f+\xi)] - \xi}{\gamma} \leq p_d - p_f \leq \mathbb{E}[\min(\Phi h_f, f)] \\ & 0 \leq p_d - p_c \leq \min(h_c, p_d - p_f + \frac{h_c - \mathbb{E}[\min(\Phi h_f, f+\xi)]}{\gamma}) \end{aligned}$$

Note that this case can hold only if $\min(h_c, \xi) > \mathbb{E}[\min(\Phi h_f, f+\xi)] - \gamma\mathbb{E}[\min(\Phi h_f, f)]$.

Therefore, we have $p_{c3} = p_{d3}$, $p_{f3} = \frac{1}{\gamma}[v - \mathbb{E}[\min(\Phi h_f, f+\xi)] - (1-\gamma)p_{d3}]$.

- If $\gamma > \alpha$, then $p_{d3} = v - \mathbb{E}[\min(\Phi h_f, f+\xi)] + \gamma\mathbb{E}[\min(\Phi h_f, f)]$.
- If $\gamma < \alpha$, then $p_{d3} = v - \mathbb{E}[\min(\Phi h_f, f+\xi)] + \gamma(\frac{\mathbb{E}[\min(\Phi h_f, f)] - \min(h_c, \xi)}{\gamma})^+$.

Again, there are two options for the optimal deposit:

(f.3.1) $f = f_3$, where f_3 is the local maximizer for the case $f \leq \phi h_f - \xi$:

$$\begin{aligned} f_3 = \arg\max_f \quad & \alpha\big[p_{f3} + (1-\beta)f - c_r(\beta)\big] + (1-\alpha)(p_{d3} - c_d) \\ \text{s.t.} \quad & \max(0, h_f - \xi) \leq f \leq \phi h_f - \xi, \\ & \mathbb{E}[\min(\Phi h_f, f+\xi)] - \gamma\mathbb{E}[\min(\Phi h_f, f)] < \min(h_c, \xi). \end{aligned}$$

Then, consumers only return the firm-owned reusable packaging when they are in the effortless-return state.

(f.3.2) $f = \phi h_f$, then consumers always return the packaging.

Let $\pi(f.1)$, $\pi(f.2)$, $\pi(f.3)$ denote the maximum profit of the above strategies (f.1), (f.2), and (f.3), respectively. We know $\pi^f = \max(\pi(f.1), \pi(f.2), \pi(f.3))$ is decreasing in $c_{r,o}$. Since the profit of the benchmark model π^b is independent of $c_{r,o}$, there must exist a threshold $\mathcal{C}^f$ such that $\pi^f > \pi^b$ if and only if $c_{r,o} < \mathcal{C}^f$. Summarizing the above discussion, we can arrive at Lemma OS.I.2.

Note that $\pi(f.2) > \pi(f.1)$ only if the firm needs to set a large discount for consumer-owned

reusable packaging ($p_d - p_c > h_c$) to ensure it can set a large discount for firm-owned reusable packaging, i.e., $p_d - p_f = \mathbb{E}[\min(\Phi h_f, f)] < p_d - p_c + \frac{\mathbb{E}[\min(\Phi h_f, f+\xi)] - h_c}{\gamma}$. Then, we have the following two conclusions:

- $\pi(f.1) > \pi(f.2)$ always holds when $\mathbb{E}[\min(\Phi h_f, f)] + \frac{h_c - \mathbb{E}[\min(\Phi h_f, f+\xi)]}{\gamma} < h_c$ holds for any $f \in [\max(h_f - \xi, 0), \phi h_f]$. Because under this condition, the firm never needs to induce type-UI consumers to use personal reusable packaging and can save on the incentive cost. This condition is equivalent to $h_c < \min_{\max(h_f-\xi,0) \le f \le \phi h_f} \frac{\mathbb{E}[\min(\Phi h_f, f+\xi)] - \gamma \mathbb{E}[\min(\Phi h_f, f)]}{1-\gamma} = H_1$.
- $\pi(f.1) > \pi(f.2)$ always holds as long as $\gamma < \alpha + (1-\alpha)\theta$ and strategy (f.1) is available. Since under this condition, it is not profitable for the firm to set a large discount for firm-owned reusable packaging.

□

Proof of Proposition OS.I.1: First, we know π^f is decreasing in $c_{r,o}$ and π^b is independent of $c_{r,o}$. Therefore, there exists a unique threshold $\mathcal{C}^f$ such that $\pi^f > \pi^b$ if and only if $c_{r,o} < \mathcal{C}^f$, defined as:

$$\mathcal{C}^f = \inf\{c_{r,o} \ge 0 \mid \pi^f \le \pi^b\}.$$

Second, similar to the proof of Proposition 1, we can still rewrite $\pi^f = g_1(\gamma) - \alpha g_2(c_{r,o}, \gamma)$, where $g_2(c_{r,o}, \gamma)$ is increasing in $c_{r,o}$. Note that $g_1(\gamma = 1) \ge v - (1-\beta)\xi - c_d > v - \xi - c_d$. Therefore, there must exist a threshold Γ_0^* such that $g_1(\gamma) > v - \xi - c_d$ if $\gamma > \Gamma_0^*$.

Furthermore, according to the proof of Lemma OS.I.1, we know $\max(\pi_0, \pi_1) > \max(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6)$ if and only if $c_d < \mathcal{C}_1^b$, where

$$\mathcal{C}_1^b = \inf\{c_d \ge 0 | \max(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6) \ge \max(\pi_0, \pi_1)\}$$

Then, under the condition $c_d < \mathcal{C}_1^b$, we know $\pi^b = v - \xi - c_d + \alpha\theta \max(0, c_d - \frac{(h_c - \xi)^+}{\gamma})$. Therefore, $\pi^f - \pi^b > 0$ if and only if $g_2(c_{r,o}, \gamma) < \frac{g_1 - (v - \xi - c_d)}{\alpha} - \theta \max(0, c_d - \frac{(h_c - \xi)^+}{\gamma})$. Since $g_2(\cdot)$ is increasing in $c_{r,o}$, its inverse $g_2^{-1}(\cdot)$ exists and is also increasing. Thus, the condition is equivalent to $c_{r,o} < \mathcal{C}^f$, where $\mathcal{C}^f$ is defined as the right-hand side composed with g_2^{-1}. Finally, inspection of the term $\mathcal{C}^f$ reveals that it is decreasing in α. Therefore, given $\alpha_1 < \alpha_2$, we know $\mathcal{C}^f|_{\alpha=\alpha_1} > \mathcal{C}^f|_{\alpha=\alpha_2}$.

□

Proof of Proposition OS.I.2: We directly focus on the case when $\gamma > \max(\alpha + (1-\alpha)\theta, \frac{\theta}{\alpha\theta + 1 - \alpha})$. According to the proof of Lemma OS.I.1, we can find that $\frac{d\pi_0}{dc_d} < \frac{d\pi_1}{dc_d} < \frac{d\pi_2}{dc_d} = \frac{d\pi_3}{dc_d} = \frac{d\pi_4}{dc_d} < \frac{d\pi_5}{dc_d} = \frac{d\pi_6}{dc_d}$. Then, there exists a threshold $\mathcal{C}^*$ such that it is optimal for the firm to choose either strategy (b.6) or (b.5) if and only if $c_d > \mathcal{C}^*$, where

$$\mathcal{C}^* = \inf c_d \ge 0 \mid \max(\pi_5, \pi_6) > \max(\pi_0, \pi_1, \pi_2, \pi_3, \pi_4)$$

Then, $\pi(b.5) = \theta(v - \frac{h_c}{\gamma}) + (1-\alpha)(1-\theta)(v - c_d)$ and $\pi(b.6) = (\theta + \alpha(1-\theta))(v - \frac{k + h_c}{\gamma}) + (1-\alpha)(1-\theta)(v - c_d)$. Then, there exists a H_2 such that $\pi(b.6) > \pi(b.5)$ if and only if $h_c < H_2$, where

$$H_2 = \frac{[\theta + \alpha(1-\theta)](\gamma v - k) - \theta\gamma v}{\alpha(1-\theta)}$$

Furthermore, according to the proof of Lemma OS.I.2, we know that $\pi(f.2) < \pi(f.1)$ when $h_c < \frac{\mathbb{E}[\min(\Phi h_f, f_2 + \xi)] - \gamma \mathbb{E}[\min(\Phi h_f, f_2)]}{1-\gamma}$.

Let $\mathcal{H}^* = \min(\frac{\mathbb{E}[\min(\Phi h_f, f_2+\xi)]-\gamma\mathbb{E}[\min(\Phi h_f, f_2)]}{1-\gamma}, H_2)$. Then, under the condition $c_d > \mathcal{C}^*$ and $h_c < \mathcal{H}^*$, the firm will choose strategy (b.6) in the benchmark model, and choose strategy (f.1) or (f.3) in the model with firm-owned reusable packaging. Then, $W^b = (1-\alpha)(1-\theta) < 1-\alpha \leq W^f$ always holds. □

Proof of Proposition OS.I.3: First, we know that $\pi(f.1), \pi(f.2), \pi(f.3)$ are decreasing in h_c. However, strategy (f.3) is not feasible when $h_c < \mathbb{E}[\min(\Phi h_f, f_3+\xi)] - \gamma\mathbb{E}[\min(\Phi h_f, f_3)]$.

To prove that the optimal profit $\pi^f = \max\{\pi(f.1), \pi(f.2), \pi(f.3)\}$ remains decreasing in h_c, it suffices to show that strategy (f.3) is not the unique global maximum at the point where it becomes infeasible.

Note that $\pi(f.3) < \pi(f.1)$ when $h_c < \mathbb{E}[\min(\Phi h_f, f_3+\xi)]$. Therefore,

- When $h_c \geq \mathbb{E}[\min(\Phi h_f, f_3+\xi)]$, $\pi^f = \max(\pi(f.1), \pi(f.2), \pi(f.3))$;
- when $\mathbb{E}[\min(\Phi h_f, f_3+\xi)] - \gamma\mathbb{E}[\min(\Phi h_f, f_3)] \leq h_c < \mathbb{E}[\min(\Phi h_f, f_3+\xi)]$, then $\pi^f = \max(\pi(f.1), \pi(f.2), \pi(f.3)) = \max(\pi(f.1), \pi(f.2))$.
- When $h_c < \mathbb{E}[\min(\Phi h_f, f_3+\xi)] - \gamma\mathbb{E}[\min(\Phi h_f, f_3)]$, then $\pi^f = \max(\pi(f.1), \pi(f.2))$.

Combining these cases, strategy (f.3) ceases to be the optimal choice before it becomes infeasible. Therefore, the transition is smooth, and π^f is monotonically decreasing in h_c across the entire domain. □

Proof of Proposition OS.I.4: Note that strategy (f.1) is not available if $h_f < \bar{h}_f = \frac{(1-\gamma)h_c}{\mathbb{E}[\Phi]}$. Therefore,

- If $h_f \geq \bar{h}_f$, then $\pi = \max(\pi(f.1), \pi(f.2), \pi(f.3))$.
- If $h_f < \bar{h}_f$, then $\pi = \max(\pi(f.2), \pi(f.3))$.

Therefore, as long as the profit when h_f approaches $\bar{h}_f$ from the left is strictly smaller than the profit when h_f approaches $\bar{h}_f$ from the right, i.e., $\pi(h_f \to (\bar{h}_f)^-) < \pi(h_f \to (\bar{h}_f)^+)$, there must exist $h_{f1} < \bar{h}_f < h_{f2}$ such that $\pi(h_f = h_{f1}) < \pi(h_f = h_{f2})$.

Note that $\pi(f.2) < \pi(f.1)$ always holds if $\gamma \leq \alpha + (1-\alpha)\theta$ for any $h_{f2} > \bar{h}_f$, since it is never profitable to set $p_d - p_c \geq h_c$ under this condition. Given this condition, we only need to prove that $\pi(f.1)|_{h_f=\bar{h}_f} > \pi(f.3)|_{h_f=\bar{h}_f}$. Let f_1^* and f_3^* denote the optimal deposit under strategy (f.1) and (f.3), respectively.

$$\pi(f.1)_{h_f=\bar{h}_f} = v - (1-\gamma)h_c - \alpha\theta h_c - \alpha(1-\theta)(c_r(\rho(f_1^*)) - f_1^*\mathbb{E}[I_{\Phi h_f > f_1^*+\xi}]) - (1-\alpha)c_d$$

$$\pi(f.3)_{h_f=\bar{h}_f} = v - (1-\gamma)h_c + (\gamma-\alpha)\mathbb{E}[\min(\Phi h_f, f_3^*)] - \alpha(c_r(\rho(f_3^*)) - f_3^*\mathbb{E}[I_{\Phi h_f > f_3^*+\xi}]) - (1-\alpha)c_d$$

According to the above function, we know $f_3^* \geq f_1^*$ must hold. Then, $\tau(\rho(f_3^*)) \geq \tau(\rho(f_1^*))$. As a result, $\frac{d\pi(f.3)}{dc_{r,o}} = -\alpha(1-\frac{1}{\tau(\rho(f_3^*))}) < -\alpha(1-\theta)(1-\frac{1}{\tau(\rho(f_1^*))}) = \frac{d\pi(f.1)}{dc_{r,o}} < 0$.

Let $\Gamma_1^* = \alpha + (1-\alpha)\theta$. Then, we know there exist a threshold $\mathcal{C}_1^*$ such that $\pi(f.1)_{h_f=\bar{h}_f} > \pi(f.3)_{h_f=\bar{h}_f}$ if $c_{r,o} > \mathcal{C}_1^*$ and $\gamma < \Gamma_1^*$. In this way, there exist $h_{f1} < \bar{h}_f < h_{f2}$ such that $\pi^f(h_f = h_{f1}) < \pi^f(h_f = h_{f2})$.

Note that we can also consider the extreme case where $\gamma = 0$. In this scenario, the firm will never

offer a discount for any form of reusable packaging. More generally, since the firm's decision regarding incentive provision is continuous in γ, it follows that for sufficiently small values of γ, the firm will also choose not to offer any incentives. Under these conditions, only cases (f.1) and (f.3) remain relevant. In other words, when h_f is large, type-CI consumers will choose personal reusable packaging (i.e., case (f.1)); when h_f is small, type-CI consumers will choose firm-owned reusable packaging (i.e., case (f.3)). In this setting, type-CI consumers will voluntarily switch from consumer-owned reusable packaging to firm-owned reusable packaging when h_f falls below a certain threshold. Although a lower h_f enables the firm to charge a higher price, this behavioral shift increases the firm's total packaging cost.

□

Proof of Proposition OS.I.5: We examine the impact of the consumer hassle cost, h_c, on the firm's total waste, W^f. Based on the analysis in Lemma OS.I.2, the properties of the firm's profits are:

- $\pi(f.3)$ is independent of h_c.
- $\pi(f.2)$ is strictly decreasing in h_c.
- $\pi(f.1)$ is strictly decreasing in h_c, and is feasible only when $h_c < \frac{\mathbb{E}[\Phi]h_f}{1-\gamma}$.

We focus on the scenario where a decrease in h_c triggers the firm to switch from strategy (f.2) to (f.1). The following analysis provides the sufficient conditions for this transition and compares the resulting environmental outcomes.

Consider the critical point $h_c = h_{c2} \equiv \frac{\mathbb{E}[\Phi]h_f}{1-\gamma}$. At this threshold, strategy (f.1) is not feasible, so the firm chooses between (f.2) and (f.3). Comparing the sensitivity of profits to the cost of disposables (c_d), we observe:

$$\frac{d\pi(f.2)}{dc_d} = -(1-\alpha)(1-\theta) > -(1-\alpha) = \frac{d\pi(f.3)}{dc_d}.$$

Consequently, there exists a threshold $\mathcal{C}_2^*$ such that if $c_d > \mathcal{C}_2^*$, then $\pi(f.2) > \pi(f.3)$ at $h_c = h_{c2}$. Thus, the firm chooses strategy (f.2) at this point.

Consider any $h_c = h_{c1} < \frac{\mathbb{E}[\Phi]h_f}{1-\gamma}$. Strategy (f.1) becomes feasible. According to Lemma OS.I.2, $\pi(f.1) > \pi(f.2)$ holds when $\gamma < \alpha+(1-\alpha)\theta$. Furthermore, since $\pi(f.1)$ and $\pi(f.2)$ are decreasing in h_c while $\pi(f.3)$ is constant, the condition established in Step 1 (where $\pi(f.2) > \pi(f.3)$ at the threshold) implies that $\pi(f.1) > \pi(f.2) > \pi(f.3)$ for h_{c1}. Therefore, under the condition $\gamma < \alpha + (1-\alpha)\theta$, the firm switches to strategy (f.1) when h_c drops to h_{c1}.

To ensure the price discrimination effect of firm-owned reusable packaging is significant, we focus on the case where $\gamma > \alpha$.

Finally, we compare the environmental outcome when the firm changes from (f.2) to (f.1). For simplification, we assume ϕ is sufficiently large such that the firm sets a small deposit, inducing consumers to return packaging only in the effortless-return state. Under this case, we define $\Gamma_2^* = \alpha$ and $\Gamma_3^* = \alpha + (1-\alpha)\theta$. Then, $W^f(h_c = h_{c2}) = (1-\alpha)(1-\theta) + \alpha(1-\theta)(1-\beta)$ and $W^f(h_c = h_{c1}) = 1 - \alpha + \alpha(1-\theta)(1-\beta)$. Thus, we have $W^f(h_c = h_{c1}) > W^f(h_c = h_{c2})$. In other cases, we define $\Gamma_2^* = \Gamma_3^* = \alpha + (1-\alpha)\theta$ such that $\Gamma_2^* < \gamma < \Gamma_3^*$ is an empty set.

To sum up, there exist $h_{c1} < h_{c2}$ such that W^f increases when h_c decreases from h_{c2} to h_{c1} if $\Gamma_2^* < \gamma < \Gamma_3^*$ and $c_d > \mathcal{C}_2^*$.

□

Proof of Proposition OS.I.6: When the firm offers its reusable packaging, the possible optimal solutions are listed in the proof of Lemma OS.I.2. Since we know $\pi(f.1) > \pi(f.2)$ when $\gamma = 1$ and both of them are continuous functions of γ, there must exist a threshold $\Gamma_3^* < 1$ such that $\pi(f.1) > \pi(f.2)$ when $\gamma > \Gamma_3^*$ for any available h_c. Under this case, the optimal solution is similar to that of Lemma 3. Then, we can get the same conclusion. □