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Abstract

A significant portion of the food loss in agricultural supply chains occurs at the farm level and has been linked to high cosmetic standards adopted by retailers regarding the size, color, and shape of the produce. We examine the economic incentives for retailers to adopt such high standards and their impact on food loss. We build a sequential game between a retailer and a farmer, where the retailer signs a contract with the farmer specifying both the wholesale price and cosmetic quality standard. Setting a high standard allows the retailer to sell the products at a price premium but increases the rejection rate, i.e., reduces the proportion of produce that satisfies this standard. We find that compared to a low cosmetic standard, a high standard does not always increase food loss and could lower food loss when the price premium is high and the relative difference between the rejection rates under both standards is low. Consequently, banning cosmetic standards may backfire and increase food loss instead. When retailers set a high cosmetic standard, we find that an effective policy intervention is to reduce the rejection rate under the high standard by, e.g., investment in agriculture research. We confirm and add to these results and policy implications in the presence of yield-enhancing efforts, an alternative sales channel, and harvesting cost variability.

Keywords: Food loss, cosmetic standard, agriculture contract, government policy

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1. Introduction

Based on the Food and Agriculture Organization of the United Nations, about one third of food produced globally is wasted (Gustavsson et al. 2011), which occurs in all stages of the agriculture supply chain, from the downstream at the consumers and retailers, all the way up to the upstream, at the distributors or on farms. The wasted produce upstream frequently does not leave the farm, where it is plowed under, composted, or converted to animal feed. Removing such produce from human consumption wastes resources such as water, energy, and fertilizer and can exacerbate climate change by generating greenhouse gas emissions, such as methane, more potent than carbon dioxide.

It is suggested that one important cause of food loss upstream is the use of high cosmetic standards (Gustavsson et al. 2011, Parfitt et al. 2010), reported to account for approximately 20% of the total food loss globally (Gustavsson et al. 2011) and over one third in Europe (Porter et al. 2018).[1] Such standards are product descriptions meant to facilitate trade, i.e., to provide a common vocabulary for business transactions (US Environmental Protection Agency 1992, Mattsson 2014). A major aspect of these standards concerns the cosmetic features of the produce regarding weight, size, shape, and color. For instance, based on these cosmetic attributes, strawberries for fresh consumption are classified as "extra", "class I", and "class II" (the minimum allowed) in the E.U., but major retailers in Sweden rarely sell fresh strawberries below class I (Mattsson 2014). Yet failure to meet the cosmetic standards does not reduce the produce's functional or intrinsic quality, such as taste, texture, and nutrients, and often does not affect operational efficiency in packaging and transportation (Mattsson 2014, Gellynck et al. 2017, de Hooge et al. 2018). In sum, retailers frequently set cosmetic standards higher than the minimum regulatory standard.

One major reason retailers adopt such high standards is the consumers' willingness-to-pay for aesthetically-pleasing produce (de Hooge et al. 2018, Richards and Hamilton 2020). For instance, it is estimated that apples graded "extra fancy" over the grade "fancy" in Canada have a price premium of \$1.50 even for packing houses (Carew and Smith 2004). Similar price premiums are observed in the U.S. (USDA, Agricultural Marketing Service 2022).

This paper aims to present a parsimonious model to examine the adoption of high standards by the retailers and the policy implications for food loss reduction. Specifically, we consider the following tradeoff faced by a retailer: By setting a high standard, the retailer can charge a price premium compared to produce of a low standard; however, the retailer suffers a greater rejection rate, i.e., the rate at which produce that does not satisfy the standard is rejected. We are interested in examining the impact of cosmetic standards on food loss and how food loss is affected by parameters such as the price premium and the relative difference between the rejection rates under both standards. We leverage these results to generate policy insights in combating food loss.

We examine these questions in the context of contract farming, which has become increasingly common in the agricultural supply chain (Federgruen et al. 2019). For instance, in the U.S., contract

[1] Note that we use food loss instead of food waste because the latter is mostly used for wastage in the downstream of the food supply chain.

farming constituted more than 39% of agricultural production by value in 2008 (MacDonald 2011), reaching more than 90% of "novel" produce such as organics or heritage varieties. This is beneficial for both the farmer and the retailer to hedge against the risk of uncertain spot market prices and for the retailer to ensure the desired quality from the farmer (Hueth et al. 1999).

To this end, we model the interaction between a retailer and a farmer as a Stackelberg game. The retailer signs a contract with the farmer, specifying the wholesale price and cosmetic standard. Then the farmer determines the effort level, which affects the proportion of the yield that satisfies the cosmetic standard. Examples of such efforts include using better seeds, protective bags, frost fans to reduce frost damage, or greenhouse production to control temperature and humidity (de Hooge et al. 2018, Trilnick and Zilberman 2021). At the end of the growing season, the farmer harvests the proportion of yield that satisfies the standard, and the retailer sells the qualifying produce to end-consumers, where the selling price includes a premium if the standard is high.

We contribute to the literature by examining the food loss in the upstream supply chain due to the cosmetic standard set by the retailer. Though there exists qualitative work that examines the retailer's incentives to set a high standard (de Hooge et al. 2018), there is no analytical work that examines retailers' incentives via their interaction with farmers nor how this interaction affects food loss. We build a model that captures the relevant market features and delve into the link between the retailer and the farmer. This significantly differs from the more commonly studied role of consumer behavior or retailer and manufacturer inventory management on food waste in the downstream supply chain (e.g., Belavina et al. 2017, Belavina 2021, Akkas et al. 2019, Akkaş and Honhon 2022). This gives rise to different policy interventions to reduce food loss which is caused by high cosmetic standards due to the interaction between farmers and retailers.

We characterize the conditions under which the retailer sets a high cosmetic standard in equilibrium: When the relative difference in the rejection rate between both standards is low and the price premium is high, the retailer sets a high standard and a high wholesale price to induce the farmer to exert a high effort level. Otherwise, the retailer sets a low standard and wholesale price to induce the farmer to exert a low effort. We also show as the rejection rate difference increases, the equilibrium food loss does not always increase. Similarly, as the price premium increases, the equilibrium food loss does not always increase.

More importantly, we show that compared to setting a low standard, the retailer setting a high standard may not necessarily lead to a higher food loss but may decrease food loss instead. This is because when the retailer sets a high standard, the retailer also sets a high wholesale price to induce the farmer to exert a higher effort, which lowers food loss. We show that when the price premium is high and the rejection rate difference is low, the food loss reduction from the farmer's higher effort outweighs the food loss increase due to a high rejection rate from a high standard. As high cosmetic standards have been linked to significant food loss (Gustavsson et al. 2011, Parfitt et al. 2010), it is naturally assumed that a high standard may result in a higher food loss compared to a low standard. Our result challenges this straightforward assumption and shows that it is not necessarily true.

Our results point to important insights regarding possible policy interventions to reduce food loss: (1) Despite ongoing policy debates on the removal of high cosmetic standards, our results show that the policy of banning high standards needs to be used carefully, as it may backfire and increase food loss when the relative rejection rate difference between both standards is low and the price premium is high. (2) Policymakers also have to be careful about interventions that reduce the price premium for aesthetic quality, such as public campaigns to educate consumers on the distinction between nutritional and cosmetic aspects of produce, as this may increase food loss due to the retailer decreasing the wholesale price and thus lowering the farmer's effort. (3) Reducing the rejection rate under the high standard by policy intervention, such as investment in agriculture research and development, is the most preferred option among all three discussed. This intervention can achieve the lowest amount of food loss among all three policies when it can reduce the rejection rate difference to below a certain threshold.

We also extend our base model to consider three salient features of the produce market: The presence of a yield-enhancing effort, an alternative sales channel, or harvesting cost variability. We confirm the results and policy recommendations of our base model with the following additions. First, in the presence of yield effort, a ban on high cosmetic standards may become the sole viable option to reduce food loss in some circumstances. Second, the existence of an alternative sales channel reduces food loss compared to the base model as expected, but as the proportion of produce that can be sold in the alternative channel increases, the food loss does not change in a monotonic fashion. Finally, compared to the base model, the presence of harvesting cost variability may increase or decrease food loss, and this impact on food loss is non-monotonic as the variability increases. For a range of intermediate cost variability values, the policy intervention resulting in the lowest food loss may be to force the retailer to set a high standard.

The rest of the paper is organized as follows: We review the related literature in §2. In §3, we present our base model capturing the interaction between the retailer and the farmer. In §4, we characterize the equilibrium by first specifying the farmer's optimal effort decision and then the retailer's optimal contract decision. In §5, we characterize the food loss in equilibrium and compare food loss under both high and low standards, and present policy insights. In §6, we extend the base model in three directions by incorporating the yield-enhancing effort, an alternative sales channel, and harvesting cost uncertainty, and also discuss related policy insights. In §7, we conclude and discuss policy implications to curb food loss. All proofs are relegated to the Online Appendix.

2. Literature review

Our paper contributes to two streams of literature, food loss/waste in the Operations Management (OM) field and agricultural contracting.

As highlighted in Akkaş and Gaur (2022), there is a small yet growing literature on food loss/waste in OM. However, most of this literature focuses on food waste arising in the downstream of the supply chain (Luo et al. 2022). They consider how food waste is affected by different aspects of retail and manufacturing operations. For instance, Belavina et al. (2017) examine two different business models for online grocery retailing and show that subscription models reduce order quantities and cut household food waste. Astashkina et al. (2019) examine the advent of online grocery shopping compared to brick-and-mortar stores and show that it is generally beneficial to the environment when jointly considering food waste and greenhouse gas emissions by households and retailers. Belavina (2021) study the density of retailer grocery stores and find that low grocery story density increases food waste by households whereas high density increases food waste by the retailers. Akkas et al. (2019) empirically identify the contribution of operational decisions on food waste by retailers. Subsequent papers analyze the retailer's shelf space allocation (Akkaş 2019), manufacturers' salesforce compensation design (Akkaş and Sahoo 2020), manufacturers' inventory issuing policy to retailers (Akkaş and Honhon 2022), the retailer's management of ready-made food in grocery stores (Park et al. 2022), and the retailer's promotion scheme of buy-one-get-one-free (Wu and Honhon 2022), and quantify food waste due to expiration at the retailer (Jain et al. 2023).

Within the OM literature, to the best of our knowledge, only two papers consider food loss in the upstream supply chain at the farmer level. Ata et al. (2019) design volunteer-staffing policies for gleaning operations, i.e., harvesting produce left unharvested by the farmers. Different from this paper, we analyze the economic reasons arising from the interaction between the retailer and the farmer that lead to the farmer not harvesting the produce in the presence of cosmetic standards. Hezarkhani et al. (2023) study selling ugly produce under different sales channels when the cosmetic standard is exogenously given. Different from this paper, we focus on how the retailer sets the cosmetic standard and its impact on food loss. Moreover, we study the policy implications of cosmetic standards and discuss actionable levers to reduce food loss.

While the link between high cosmetic standards and food loss has been highlighted (Gustavsson et al. 2011, de Hooge et al. 2018, Devin and Richards 2018), there is very limited analytical work that has studied the economic motives behind the retailer's high cosmetic standard and the associated food loss. Richards and Hamilton (2020) study the impact of the retailer's cosmetic standard on food loss from the retailer's interaction with customers. In particular, in the presence of heterogeneous consumer utility towards cosmetic quality, they show that the retailer price-discriminates by choosing a high standard and a high selling price for consumers with a high utility for cosmetic quality. When setting a high standard is costly, the retailer may set an excessively high price for the chosen quality level, which causes food waste at the retail store. Different from this paper, the retailer sets a high standard due to its interaction with the farmer.

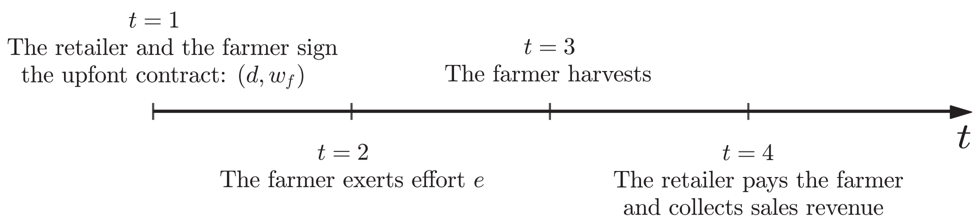
Our paper is also related to the agricultural contract literature. For instance, Huh and Lall (2013) examine the farmer's crop planning decision in the context of contract farming considering the crop price and rainfall uncertainty. Federgruen et al. (2019) discuss how a manufacturer should select a set of farmers to whom to offer a menu of contracts and propose algorithms to solve the large-scale problem efficiently. de Zegher et al. (2019) study the agriculture contract design problem in the presence of two sourcing channels to motivate farmers to adopt good farming practices that may create shared value. In all these papers, quality is irrelevant. In contrast, (cosmetic) quality is essential in the contract design of our paper, which the retailer uses to motivate the farmer's efforts. In addition, unlike this literature, we focus on the implication of contract farming on food loss.

3. Model

We model a produce supply chain consisting of a retailer and a farmer, where the retailer (she) offers a contract to the farmer (he) specifying the wholesale price and the minimum required cosmetic standard of the produce. Then the farmer determines his farming efforts, which affect the produce's cosmetic quality, and harvests only the qualifying produce, as the retailer rejects all produce that does not meet the minimum standard.

We represent the interaction between the retailer and the farmer on the timeline from $t = 1$ to $t = 4$ in Figure 1. At $t = 1$, prior to the crop growing season, the retailer sets the wholesale price $w_f \geq 0$ and the cosmetic standard d. In practice, the cosmetic quality of fresh produce is graded discretely, for example, apples can be classified by the U.S. Department of Agriculture (USDA) based on their color, size, and number of blemishes, either as "extra fancy", "fancy", "no. 1", or "utility" (USDA 2019). For simplicity, we model the retailer's cosmetic standard decision as a binary variable $d \in \{0, 1\}$, where $d = 1$ ($d = 0$) represents a high (low) cosmetic standard. We assume that the retailer does not price-differentiate based on cosmetic quality levels *within* its stores, as the low cosmetic quality produce may cannibalize the sales of high cosmetic quality counterparts.[2] The farmer accepts the contract if the profits from participating in the contract are higher than the reservation utility, which we normalize to zero.

Figure 1: Timeline of events



At $t = 2$, after signing the contract, the farmer determines the cosmetic quality effort e with $e \in [0, 1]$, which can increase the proportion of the yield which satisfies the specified cosmetic standard. As mentioned in the Introduction, examples of such efforts include using better seeds (e.g., tomato seeds destined for the fresh market are more disease-resistant than seeds for the processing market), protective bags (e.g., foam mesh) when fruits are growing, frost fans to circulate air to reduce frost damage in fruits (Trilnick and Zilberman 2021), or greenhouse production where the temperature and humidity are better controlled compared to open-air production (de Hooge et al. 2018). While exerting such efforts, the farmer incurs a quadratic cost of effort ke^2 with $k > 0$, reflecting that it becomes more costly to exert a higher effort: In reality, the farmer exhausts the low-cost efforts before using higher-cost efforts (Allen and Lueck 1995).

Given the farmer's effort e, the proportion of produce satisfying the retailer's cosmetic standard d is as follows: At a low standard (i.e., $d = 0$), this proportion is e; at a high standard (i.e., $d = 1$), the effectiveness of the farmer's effort is reduced by η—the relative difference in the rejection rate between both the high and low standards, with $0 \leq \eta < 1$—and this proportion is $(1 - \eta)e$. Combining these two cases, we can write the proportion of the produce satisfying a given standard d as $(1 - \eta d)e$, and thus that failing the standard is $1 - (1 - \eta d)e$. Here we implicitly assume that yield (crop production quantity per acre) is normalized to one and not affected by the farmer's efforts. We discuss the extension where the farmer can exert efforts to increase yield in §6.1. We also implicitly assume that yield is deterministic, as the absence of yield uncertainty can help sharpen the focus on the interaction between the retailer and the farmer.

[2]Though in practice, some retailers may sell piles of wonky produce below the usual cosmetic standard, such practices are not common and are on an ad-hoc basis.

Table 1: Cosmetic Quality Grading Facts

	Tomato	**Cucumber**	**Strawberry**	**Broccoli**	**Apple**
Cosmetic standards	Size, color	Length, color, shape	Size, color	Size, color	Size, color
Grading	At packing location	In the field	In the field	Not available	Not available
Fresh market rejection rate	2.5%	4%	7%	9%	18%

-Data on cosmetic standards and grading are from https://www.wifss.ucdavis.edu/materials/#produce-section1f117-335c for tomatoes, cucumbers, and strawberries and from https://extension.psu.edu/broccoli-production and https://extension.psu.edu/apple-production for broccoli and apples.
-Data on fresh market rejection rates are from Gellynck et al. (2017).

At the end of the crop growing season, at $t = 3$, the farmer determines the proportion of produce to harvest with a unit harvesting cost c. Note that we assume $c \leq w_f$ to ensure that the farmer is willing to participate in the contract. The harvest proportion is limited by the qualifying yield rate, i.e., $(1 - \eta d)e$, which we can easily show is also the optimal harvest proportion. Note that we assume that produce that falls below the cosmetic standard is not sold to an alternative channel; we relax this assumption in §6.2. We also assume the harvesting cost is deterministic and relax this assumption to represent the reality that the harvesting cost can be stochastic in §6.3.

In the last stage, i.e., at $t = 4$, the retailer buys all qualifying produce from the farmer at unit wholesale price w_f. The retailer sells the produce to end-consumers at a unit price p if $d = 0$ or $p + \delta$ if $d = 1$. In other words, δ is the price premium consumers are willing to pay for aesthetically-pleasing produce meeting a high standard over that meeting only a low standard. Therefore, given d, the unit selling price is $p + \delta d$. Such a premium for cosmetically-pleasing produce is observed in practice (de Hooge et al. 2018, Richards and Hamilton 2020, USDA, Agricultural Marketing Service 2022). Note that we assume the retailer can always sell all the qualifying produce, and thus we do not specify the purchasing quantity in the contract. We relax this assumption in §5.4 by endogenizing the retail price and show that the analytical and policy insights in the base model continue to hold.

Table 1 provides more context for the model features with examples of the cosmetic standard criterion, grading location, and actual rejection rate for some common fruits and vegetables. We observe that cosmetic standards are mostly based on size, color, length, and shape. Grading the produce into cosmetic standards is done either during harvesting in the field (i.e., the produce below the standard is not harvested) or during packing at the farm or a centralized location. This grading step filters a significant portion of the produce out of the fresh market, which can range from a relatively low 2.5% for tomatoes to a high of 18% for apples.

4. Characterizing the Farmer and Retailer's Optimal Decisions

To solve the base model, we start with the farmer's optimal effort, followed by the retailer's optimal contracting decision. To avoid solutions where the farmer sets maximum effort in equilibrium, we assume the effort cost is large enough, i.e., $4k > p + \delta - c$. This assumption does not qualitatively affect our main results but precludes results solely due to the maximum-effort effects.

4.1 Farmer's Optimal Effort

At time $t = 2$, given the contract parameters (d, w_f), the farmer maximizes his profit by choosing the optimal effort level, denoted by $e^*(d, w_f)$, as follows:

$$e^*(d, w_f) = \underset{e \in [0,1]}{\operatorname{argmax}} \left\{ (w_f - c)(1 - \eta d)e - ke^2 \right\}, \tag{1}$$

where the first term is the product of the farmer's unit profit margin (wholesale price minus harvesting cost) and the total qualifying harvested proportion; and the second term is the effort cost. Lemma 1 characterizes this optimal farmer effort.

Lemma 1 *The farmer's optimal effort* $e^*(d, w_f) = \frac{(1-\eta d)(w_f - c)}{2k}$ *if* $k > \frac{1}{2}(1-\eta d)(w_f - c)$ *and equals* 1 *otherwise.*

As seen in Lemma 1, if the effort cost k is sufficiently large, the farmer exerts an interior effort, which increases in the unit margin $w_f - c$ and decreases in the cosmetic standard d, rejection rate difference η, and effort cost k. Otherwise, the farmer exerts maximum effort, which will not emerge in equilibrium (see §4.2 below).

4.2 Retailer's Optimal Contracting Decision

At $t = 1$, the retailer takes into account the farmer's best-response harvesting and effort level decisions to set the contract terms (d, w_f) that maximize her profit. We solve the retailer's optimal contracting decision by first fixing the standard decision d to solve for the optimal wholesale price, and then solving for the optimal d. Given d, we can write the retailer's profit $R(d)$ resulting from the optimization over the wholesale price w_f as follows:

$$R(d) = \max_{w_f \geq c} \left[(p + \delta d - w_f)(1 - \eta d)e^*(d, w_f) \right], \tag{2}$$

where $p + \delta d - w_f$ is the unit profit margin (selling price minus wholesale price), and $(1-\eta d)e^*(d, w_f)$ is the proportion of produce sold to the retailer by the farmer. As mentioned before, the constraint $w_f \geq c$ is to ensure the participation of the farmer. We denote the optimal wholesale price for a given d as $w_f^*(d)$, i.e., $w_f^*(d) = \text{argmax}\{R(d)\}$. The retailer determines which cosmetic standard to adopt to maximize her profit by comparing the profit under both standard levels, i.e.,

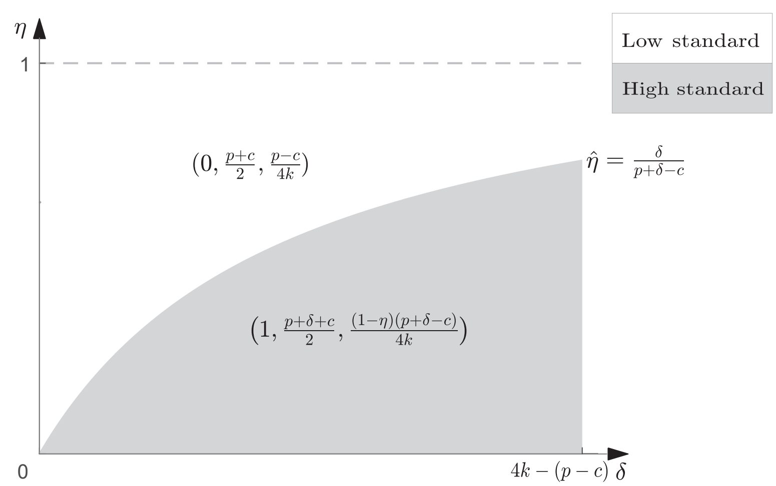
$$d^* = \text{argmax}\{R(0), R(1)\}.$$

After characterizing d^*, we can then substitute it into $w_f^*(d)$ and subsequently into $e^*(d^*, w_f^*(d))$ to obtain the equilibrium outcome, denoted by (d^*, w_f^*, e^*). For conciseness, we drop the arguments in the notation when no confusion arises. Proposition 1 below characterizes the two equilibrium outcomes that emerge.

Proposition 1 *There exists a threshold* $\hat{\eta} = \frac{\delta}{p+\delta-c}$ *such that:*

- *For* $\eta \leq \hat{\eta}$*, the retailer sets a high cosmetic quality standard* $d^* = 1$ *and wholesale price* $w_f^* = \frac{p+\delta+c}{2}$*; the farmer exerts effort level* $e^* = \frac{(1-\eta)(p+\delta-c)}{4k}$*.*
- *For* $\eta > \hat{\eta}$*, the retailer sets a low cosmetic standard* $d^* = 0$ *and wholesale price* $w_f^* = \frac{p+c}{2}$*; the farmer exerts effort level* $e^* = \frac{p-c}{4k}$*.*

Figure 2: Equilibrium outcome (d^*, w_f^*, e^*)



The equilibrium outcome characterized in Proposition 1 is illustrated in Figure 2 on the $\delta - \eta$ plane. Whether the retailer adopts a high standard depends on the relative rejection rate difference between both standards, η, compared to the relative increase in the profit margin under the high standard, $\hat{\eta} = \frac{\delta}{p+\delta-c}$: If the rejection rate difference is lower than the relative increase, the retailer optimally adopts a high standard; otherwise, the retailer adopts a low standard. The retailer's wholesale price increases in the standard but is independent of the rejection rate difference. Consequently, the farmer always exerts more effort under a high than a low standard, and his optimal effort decreases in the rejection rate difference under a high standard.

5. Food Loss

We examine how the interaction between the retailer and the farmer shapes food loss, which according to the Food and Agriculture Organization of the United Nations, is defined as "the decrease in edible food mass throughout the part of the supply chain that specifically leads to edible food for human consumption" (Gustavsson et al. 2011). We focus on the food loss in the upstream supply chain, at the farmer's, due to the interaction between the farmer and the retailer, and thus we do not consider the downstream food waste due to the retailer operations and consumer behaviors. We first characterize food loss in equilibrium and how it is affected by the relative difference in rejection rate between both standards and price premium. We then examine whether a high standard by the retailer necessarily results in a higher food loss than a low standard. We proceed to discuss the policy implication regarding combating food loss. Lastly, we examine a model where we endogenize the retail price to show that our qualitative insights and policy implications in the base model continue to hold.

In our base model, we assume all produce below the retailer's standard becomes food loss. This applies to produce where there is very limited access to an alternative sales channel, such as the processing market or farmer's market. For instance, produce such as celery, cucumber, endives, and melon have a very limited (if at all) processing market because such produce cannot be easily processed (e.g., do not freeze well). The rejected produce may be left to rot in the field or used for animal feed, biomass, or compost—products of lower value in the food recovery hierarchy. In §6.2, we relax this assumption and allow produce below the standard to be sold to an alternative sales channel. For instance, produce such as citrus fruits, tomatoes, potatoes, or other root vegetables have abundant processing options. Other than the processing market, these produce below the standard can be sold in a farmer's market or ugly product market (Akkaş and Gaur 2022).

5.1 Characterizing Equilibrium Food Loss

We measure food loss as the difference between the total yield and that sold to customers. For a given standard d, we denote by $L(d)$ the proportion of the yield that becomes food loss, which is given as follows:

$$L(d) = 1 - (1 - \eta d)e^*(d, w_f^*(d)). \tag{3}$$

We obtain food loss at the equilibrium, i.e., $L(d^*) = 1-(1-\eta d^*)e^*$ (shortened as L^*), by substituting the retailer and farmer equilibrium decisions given in Proposition 1 into Eq. (3). We characterize L^* in the corollary below:

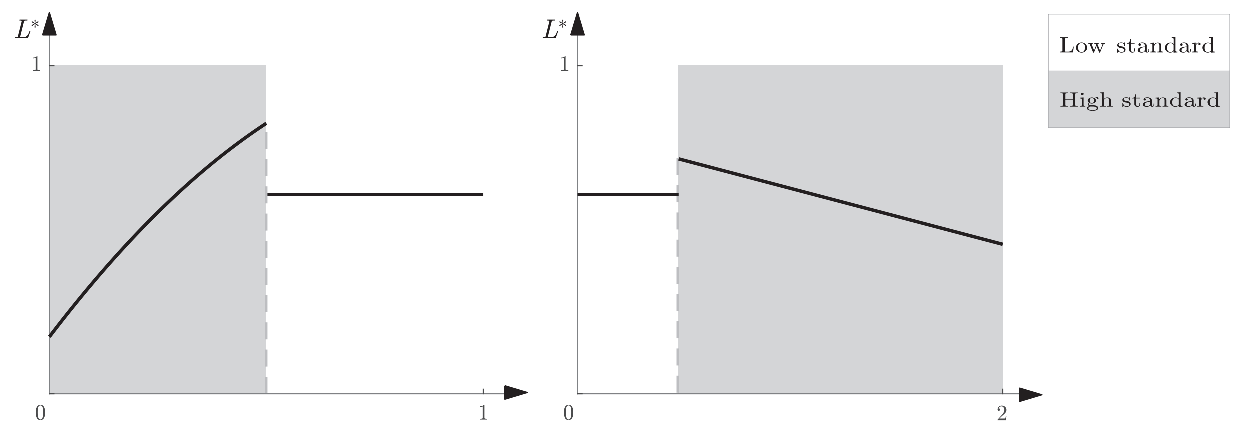
Corollary 1 *Food loss at the equilibrium is given as follows: If $\hat{\eta} \le \eta < 1$, then $L^* = 1 - \frac{p-c}{4k}$; otherwise, $L^* = 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k}$.*

We next characterize how the equilibrium food loss L^* is affected by the rejection rate difference and price premium in Proposition 2.

Proposition 2 *L^* is non-monotonic in the rejection rate difference η and the price premium δ.*

Figure 3 illustrates Proposition 2 for the rejection rate difference and price premium in Panels (a) and (b), respectively. In Panel (a), when the rejection rate difference increases, the equilibrium food loss L^* increases as the proportion of produce satisfying the high standard decreases. However, when the rejection rate difference exceeds a threshold ($\hat{\eta}$), L^* drops because the retailer optimally switches from a high standard to a low one. In Panel (b), we observe that for a low price premium δ, L^* is initially constant as the retailer optimally uses a low standard. As the price premium further increases, the food loss jumps up as the retailer optimally switches to a high standard. However, as the premium further increases, the food loss decreases because the retailer optimally raises the wholesale price to incentivize a higher farmer effort level.

Figure 3: Impact of rejection rate difference η and price premium δ on equilibrium food loss L^*



(a) Sensitivity to η (b) Sensitivity to δ

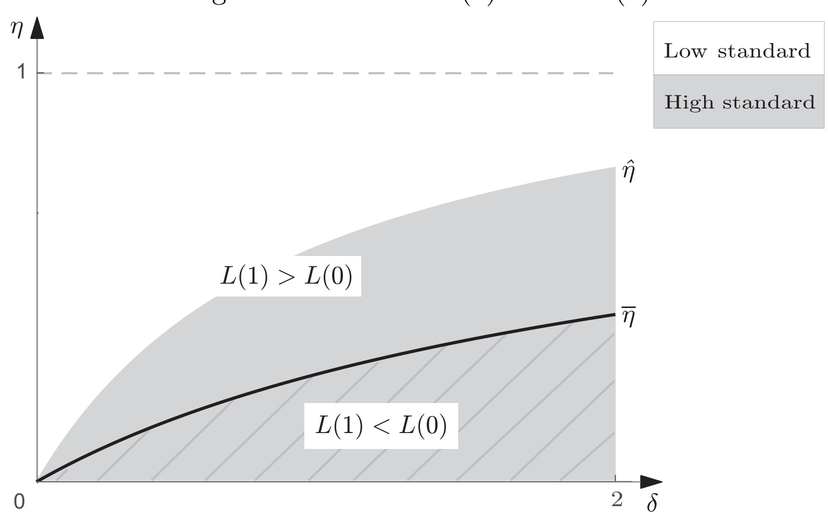
Notes. In both panels (a) and (b), $p = 7$, $c = 6$, and $k = 0.8$. In (a) $\delta = 1$; in (b) $\eta = 0.25$.

5.2 Effect of Cosmetic Standard on Food Loss

We next examine whether, ceteris paribus, the retailer setting a high cosmetic standard always results in a higher food loss than setting a low standard. As high cosmetic standards have been linked to significant food loss (Gustavsson et al. 2011, Parfitt et al. 2010), it is naturally assumed that a high standard may result in a higher food loss compared to a low standard. We examine whether this assumption is true in the following proposition by comparing food loss under both standards, i.e., $L(1)$ and $L(0)$. (Note that $L(d)$ for $d \in \{0, 1\}$ does not refer to the equilibrium food loss but refers to the food loss under a given cosmetic standard.)

Proposition 3 *There exists a threshold* $\overline{\eta} = 1 - \sqrt{\frac{p-c}{p+\delta-c}} < \hat{\eta}$ *such that for all* $\eta < \overline{\eta}$*, we have* $L(1) < L(0)$*; and* $L(1) \geq L(0)$ *otherwise.*

Figure 4: Food loss $L(1)$ versus $L(0)$



Notes. In this example, $p = 7$, $c = 6$, and $k = 0.8$.

Proposition 3 shows that the assumption that a high standard leads to greater food loss is not necessarily true. In particular, we make the following observation: *The food loss under a high cosmetic standard is lower than that under a low cosmetic standard when the price premium is large enough and the rejection rate difference is small enough.* Intuitively, this is because setting a high standard has two opposing effects: On the one hand, it increases the rejection rate compared to setting a low standard, which increases food loss; on the other hand, it causes the retailer to increase the wholesale price to induce a higher farmer effort, which decreases food loss. The net impact of this high standard is that it lowers food loss when the price premium is large enough and the rejection rate difference is small enough. Please see the case when $L(1) < L(0)$ in the striped region in Figure 4, where the rejection rate satisfies $\eta < \bar{\eta}$.

In short, contrary to common belief, though a high cosmetic standard may indeed lead to significant food loss, it does *not* mean that setting a low standard necessarily lowers food loss. We show that this observation continues to hold in all the extensions considered in §6. We next discuss the policy implication of this result together with those of previous results.

5.3 Lowering Food Loss: Policy Implications

As cosmetic quality runs through the supply chain to impact the farmer, the retailer, and the end consumer, we propose three possible policy interventions, each of which acts on one individual supply chain partner separately: (i) legislate $d = 0$ to impose a low cosmetic standard on the retailer, (ii) reduce the farmer's rejection rate difference η by reducing the rejection rate at a high standard, e.g., investing in agricultural R&D[3], and (iii) reduce the end consumer's price premium δ by, e.g., consumer outreach campaigns. We next discuss when each is effective and compare them in terms of food loss reduction to offer a final recommendation.

First, as Proposition 3 indicates that a lower cosmetic standard may not always lower food loss, banning the use of high cosmetic standards in agricultural contracts (i.e., legislating a low standard) may backfire and increase food loss instead. In particular, this occurs when the rejection rate difference is sufficiently low and the price premium is sufficiently high (i.e., $\eta < \overline{\eta}$). A ban on high standards is only effective at reducing food loss when rejection rate differences are intermediate, or $\hat{\eta} > \eta > \overline{\eta}$ (see Figure 4). Consequently, a ban should be weighed carefully.

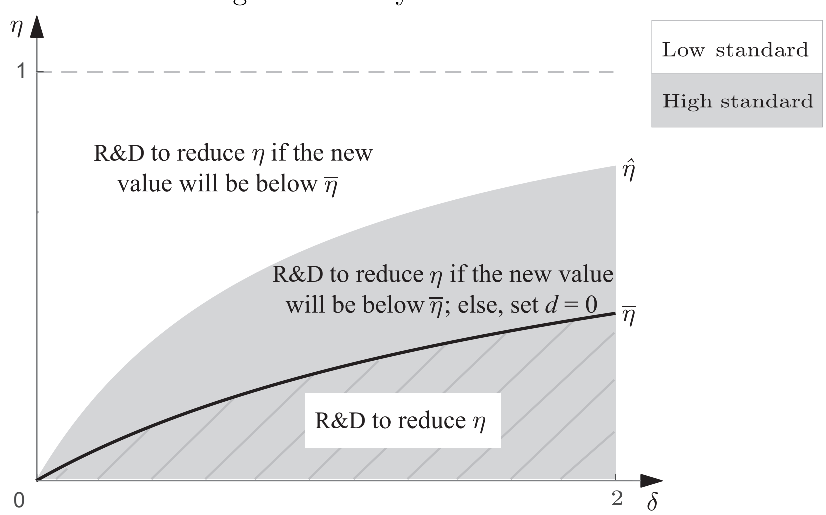
Second, the effectiveness of reducing the rejection rate difference η by investing in agricultural R&D depends on the initial and ultimate rejection rate difference. Examine Figure 3 Panel (a) and Figure 4. When the rejection rate difference is such that the retailer sets a high cosmetic standard (i.e., $\eta < \hat{\eta}$), reducing the rejection rate difference always lowers food loss. When the rejection rate difference is high (i.e., $\eta > \hat{\eta}$), reducing the rejection rate difference by a large amount (i.e., to be below $\overline{\eta}$) lowers food loss, because the effect of the lower rejection rate difference outweighs the effect of the retailer switching the standard. Reducing by a smaller amount (i.e., remaining above $\overline{\eta}$) is either ineffective if the retailer continues to set a low standard or, worse, increases food loss if the retailer switches to a high standard.

Third, as the consumer's willingness-to-pay for aesthetically-pleasing produce is commonly

[3]Note agricultural R&D could also reduce the farmer's effort cost k, which reduces food loss proportionally under both cosmetic standards (full results available upon request). We thus focus on R&D's reduction in rejection rate difference.

blamed for high cosmetic standards, we examine the effectiveness of lowering the price premium δ for a high cosmetic standard. This might be achieved through consumer education campaigns highlighting that the nutritional quality of produce is unaffected by its aesthetic quality. Similar to the second policy lever, the effectiveness of this intervention depends on the initial and ultimate price premium. Examine Figure 3 Panel (b) and Figure 4. If the price premium is high (i.e., $\delta > \frac{\eta(p-c)}{1-\eta}$), reducing the price premium by a small amount (i.e., still above $\frac{\eta(p-c)}{1-\eta}$) increases food loss: The retailer continues to set a high standard but reduces the equilibrium wholesale price, which decreases the farmer's effort. In this case, only a large reduction in the price premium (i.e., to be below $\frac{\eta(p-c)}{1-\eta}$) lowers the food loss as the retailer optimally switches to a low standard. If the price premium is low (i.e., $\delta < \frac{\eta(p-c)}{1-\eta}$), a further reduction does not change food loss as the retailer optimally always chooses a low standard.

Figure 5: Policy recommendation



Next, we combine the above three policy interventions to offer policy recommendations under different market conditions (see Figure 5). If the rejection rate difference is very low (i.e., $\eta < \overline{\eta}$), the only intervention that can reduce food loss is decreasing the rejection rate difference by reducing the rejection rate at a high standard, such as investment in agricultural R&D. For intermediate rejection rate differences (i.e., $\overline{\eta} < \eta < \hat{\eta}$), the recommended policy intervention is to reduce the rejection rate difference by R&D to be below $\overline{\eta}$. If such a reduction cannot be achieved, it is more effective to force the retailer to set a low standard. If the rejection rate difference is very high (i.e., $\eta \geq \hat{\eta}$), the only effective policy is reducing the rejection rate difference through R&D by a large amount (i.e., below $\overline{\eta}$).

To conclude, we highlight the following policy insights: (1) Banning a high cosmetic standard may backfire and lead to higher food loss. (2) Among all three policy interventions, reducing the rejection rate difference (via reducing the rejection rate at a high standard) by R&D is most preferred, as it can potentially lower the food loss to less than under a low cosmetic standard. (3) Policies aiming to reduce the price premium are never a preferred option: They achieve, at best, the same food loss as enforcing a low cosmetic standard, but may increase food loss if the premium reduction is not large enough.

5.4 Model with endogenous retail price

For simplicity, our base model assumes that the retailer can sell all the qualifying quantities from the farmer at an exogenous retailer price. We verify the robustness of this assumption by explicitly endogenizing the retail price r. To this end, we model the consumers' heterogeneous utility to be uniformly distributed over $[0, 1]$ given $d = 0$ (low standard) and over $[\mu, 1 + \mu]$ given $d = 1$ (high standard), where μ is the consumer's additional utility for produce at $d = 1$ over produce at $d = 0$. That is, the consumer's utility given any $d \in \{0, 1\}$ is uniformly distributed on $[\mu d, 1 + \mu d]$.

The timeline of this extended model is exactly the same as the base model, except that in period $t = 4$ after paying the farmer, the retailer sets the optimal r by maximizing her profit:

$$r^*(d, w_f, e) = \max_r r \min\{1 + \mu d - r, (1 - \eta d)e\},$$

where $\min\{1 + \mu d - r, (1 - \eta d)e\}$ represents the quantity that the retailer can sell given r, d, and e. This quantity is no greater than the consumer demand—as consumers buy produce if their utility exceeds r, and also no greater than the qualifying quantity $(1 - \eta d)e$. In periods $t = 2$ and $t = 3$, given the contract terms, the farmer determines the effort level $e^*(d, w_f)$ and the optimal harvesting quantity, respectively. Similar to the base model, we assume (i) the cost of effort is large enough, i.e., $4k > (1 - \eta)(1 + \mu - c - 2(1 - \eta))$, so that effort is never at the maximum level in equilibrium, and (ii) the cost of harvesting is low enough, i.e., $c < 1$, to ensure the farmer is willing to participate in the contract. In $t = 1$, the retailer optimizes over d and w_f to maximize her profits:

$$\max_{d,w_f} r^*(d, w_f, e^*(d, w_f)) \min\{1 + \mu d - r^*(d, w_f, e^*(d, w_f)), (1 - \eta d)e^*(d, w_f)\} - w_f(1 - \eta d)e^*(d, w_f),$$

where the first term is the revenue from selling to consumers, and the second term is the payment to the farmer. The following lemma characterizes the equilibrium outcomes.

Lemma 2 *There exists a threshold* $\hat{\eta}' = 1 - \sqrt{\frac{2k(1-c)^2}{2k(1+\mu-c)^2+\mu(2+\mu-2c)}}$ *such that:*

- *For* $\eta \le \hat{\eta}'$*, the retailer sets a high cosmetic quality standard* $d^* = 1$ *and wholesale price*

$w_f^* = \frac{k(1+\mu-c)}{2k+(1-\eta)^2} + c$; *the farmer exerts effort* $e^* = \frac{(1+\mu-c)(1-\eta)}{2(2k+(1-\eta)^2)}$; *and the retail price is* $r^* = \frac{(1+\mu+c)(1-\eta)^2+4k(1+\mu)}{2(2k+(1-\eta)^2)}$.

- *For* $\eta > \hat{\eta}'$, *the retailer sets a low cosmetic quality standard* $d^* = 0$ *and wholesale price* $w_f^* = \frac{k(1-c)}{2k+1} + c$; *the farmer exerts effort* $e^* = \frac{1-c}{2(2k+1)}$; *and the retail price is* $r^* = \frac{1+c+4k}{2(2k+1)}$.

We observe that in equilibrium, the retailer always sets a retail price such that she sells all the qualifying quantities from the farmer to consumers. The retailer achieves this by setting a wholesale price such that the farmer never produces more than the quantity the retailer wants to sell to consumers. This demonstrates that our assumption in the base model where all qualifying quantity is sold to consumers holds when we endogenize the retail price. Moreover, we observe in and off equilibrium that produce of high cosmetic standard always commands a price premium over produce of low cosmetic standard, and the retail price of produce of high cosmetic standard increases in the consumer's utility premium. These features, essential in our base model, result endogenously from the model when we optimize the retail price.

Lastly, we can easily show that all the qualitative insights and policy implications on food loss presented in §4 and §5 continue to hold. Therefore, we opt to use our current base model without the feature of endogenizing the retail price.

6. Model Extensions

To show the robustness of the qualitative insights on cosmetic quality and policy implications on combating food loss gleaned from our base model, we relax its three assumptions to further qualify our results. In particular, we add to the base model the following features: (1) yield-enhancing effort, (2) an alternative sales channel, and (3) harvesting cost variability. We also study the resulting policy implications.

6.1 Yield-enhancing Effort

In the base model, we assume that the farmer exerts efforts to increase only the cosmetic quality, not the yield. In this extension, we study the case when the farmer can exert separate efforts to increase quality and yield, respectively. We denote the farmer's yield-enhancing effort as a binary decision variable $a \in \{0, 1\}$, representing low or high yield effort, respectively. A low yield effort (i.e., $a = 0$) results in a yield that is normalized to one with a cost normalized to zero (there still exists a cost on cosmetic quality effort). With a high yield effort (i.e., $a = 1$), the yield is increased to y_H with $y_H > 1$, at a cost $g_H > 0$. Combining both the low and high yield efforts cases, we can write the yield as a function of a as $1 + (y_H - 1)a$. The total cost is the sum of the cost of yield efforts (i.e., ag_H) and the costs of cosmetic quality effort, which is the total yield times ke^2 (i.e., $(1+(y_H-1)a)ke^2$). We continue to assume the cosmetic quality effort is never at maximum in equilibrium, which mathematically corresponds to $4k > p+\delta-c-2g_H+2\sqrt{(p+\delta-c+g_H)g_H}$.

6.1.1 Characterizing optimal farmer and retailer decisions

Farmer's optimal quality and yield efforts. At $t=3$, given the contract terms (d, w_f), the farmer optimally harvests all the qualifying produce, the same as in the base case. At $t=2$, given the contract terms (d, w_f) and the optimal harvesting decision, the farmer simultaneously chooses the quality and yield efforts to maximize the profit as follows:

$$\max_{e\in[0,1], a\in\{0,1\}} (1+(y_H-1)a)((w_f-c)(1-\eta d)e-ke^2)-ag_H. \tag{4}$$

In the first term of Eq. (4), the farmer's profit in the base model (in Eq. (1)) is multiplied by the total yield as a function of a. When a is restricted to zero, this equation reduces to Eq. (1) in the base model. The farmer's optimal quality and yield efforts, denoted by $e^*(d, w_f)$ and $a^*(d, w_f)$, respectively, are characterized in Online Appendix A.1.

Retailer's optimal contract decision. At $t=1$, the retailer determines the cosmetic quality standard d and sets the wholesale price w_f to maximize her profit, anticipating the farmer's best response of quality and yield efforts at $t=2$. As in the base model, we first determine the retailer's optimal wholesale price for a given $d \in \{0,1\}$ as follows:

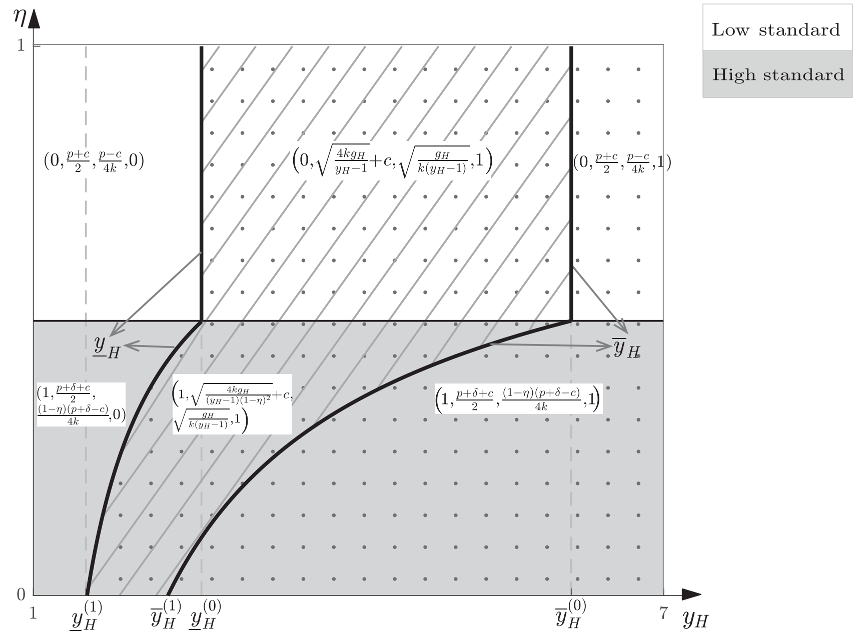
$$R(d) = \max_{w_f>c}(p+\delta d-w_f)(1-\eta d)e^*(d, w_f)(1+(y_H-1)a^*(d, w_f)). \tag{5}$$

Eq. (5) multiplies the retailer's profit margin by the qualifying produce as a function of the farmer's quality and yield efforts. We then determine the retailer's optimal cosmetic standard decision as $d^* := \text{argmax}_{d\in\{0,1\}}\{R(d)\}$. Let us denote the equilibrium outcome as (d^*, w_f^*, e^*, a^*). Proposition 4 characterizes the equilibrium for different values of y_H.

Proposition 4 *In equilibrium, the retailer's cosmetic standard decision d^* is the same as that in the base model regardless of the yield multiplier y_H. We fully characterize the two threshold functions $1 < \underline{y}_H < \overline{y}_H$ such that for $\underline{y}_H < y_H < \overline{y}_H$ the wholesale price $w_f^* = \sqrt{\frac{4kg_H}{(y_H-1)(1-\eta d^*)^2}} + c$ and the cosmetic quality effort $e^* = \sqrt{\frac{g_H}{k(y_H-1)}}$, which are larger than in the base case and decreasing in y_H; for $y_H \le \underline{y}_H$ and $y_H \ge \overline{y}_H$, both the wholesale price w_f^* and cosmetic quality e^* are equal to their respective values in the base case. The farmer sets a high yield effort $a^*=1$ iff $y_H > \underline{y}_H$.*

We present the results of Proposition 4 in Figure 6, which shows the joint impact of the yield factor y_H and rejection rate difference η on the equilibrium. Note that in this case, the retailer has

Figure 6: Equilibrium outcome (d^*, w_f^*, e^*, a^*) with yield-enhancing effort



Notes. Dotted regions correspond to a high yield effort by the farmer (i.e., $a^* = 1$); striped regions correspond to a higher wholesale price and cosmetic quality effort than in the base model.

the same two contract instruments as in the base model to induce not only the cosmetic quality effort but also the yield effort by the farmer. We find that the retailer's cosmetic standard is independent of the yield factor and continues to be determined by the rejection rate difference (see the horizontal boundary between the grey and white regions in Figure 6).

We discuss the equilibrium outcomes for different values of y_H. If the yield factor is low (i.e., $y_H \leq \underline{y}_H$), the farmer optimally does not exert yield effort, and the retailer and farmer's decisions are the same as that under the base model. If the yield factor is high (i.e., $y_H \geq \overline{y}_H$), the farmer optimally exerts a high yield effort, and the retailer's contracting and the farmer's cosmetic quality effort decisions are also the same as those under the base model. For an intermediate yield factor (i.e., $\underline{y}_H < y_H < \overline{y}_H$, the striped regions in Figure 6), the retailer optimally increases the wholesale price w_f above that in the base case. The higher margin motivates the farmer to invest in both higher yield *and* higher cosmetic quality efforts than in the base model.

6.1.2 Impact of yield-enhancing effort on food loss

We examine how food loss is affected by the new model feature, the yield factor. Similar to the base model, we can write the food loss given d as follows:

$$L(d) = (a^*(d, w_f^*(d))y_H + 1 - a^*(d, w_f^*(d)))(1 - (1 - \eta d)e^*(d, w_f^*(d))).$$

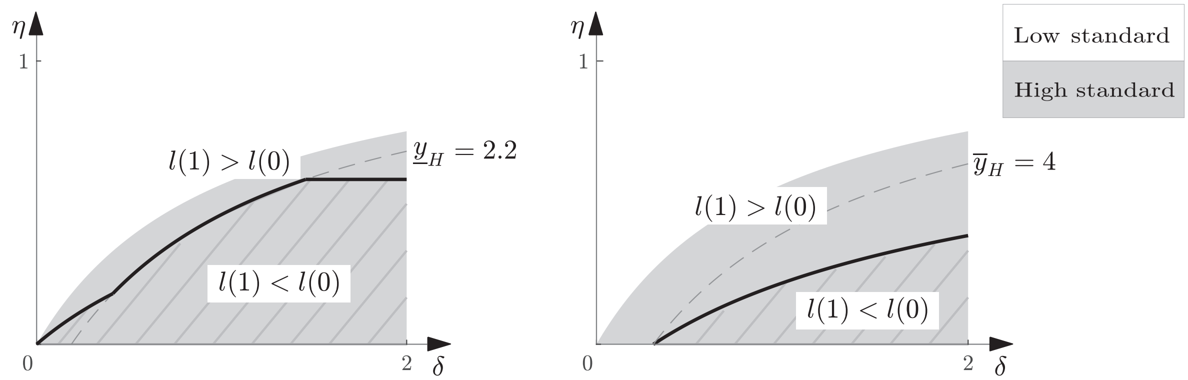
Also similar to the base model, we denote by L^* the food loss at equilibrium (d^*, w_f^*, e^*, a^*), i.e., $L^* = L(d^*)$. As yield effort increases yield, we can easily show that in the presence of yield effort, L^* is constant in y_H when $y_H < \underline{y}_H$ and increasing otherwise. Then, we examine the total food loss relative to the total yield, i.e., $l(d) = L(d)/(a^*(d, w_f^*(d))y_H + 1 - a^*(d, w_f^*(d))) = 1 - (1 - \eta d)e^*(d, w_f^*(d))$. We denote $l^* = l(d^*)$. Proposition 5 characterizes l^* and compares it with that under the base model. Note in the base model, the relative food loss is the same as the absolute food loss, as yield is normalized to one without loss of generality.

Proposition 5 *Compared to the base model, the relative food loss l^* is the same for $y_H \leq \underline{y}_H$ and $y_H \geq \overline{y}_H$, and lower for $\underline{y}_H < y_H < \overline{y}_H$. l^* is increasing in the yield factor y_H for $\underline{y}_H < y_H < \overline{y}_H$ and constant otherwise.*

As seen in Proposition 5, the relative food loss remains the same as in the base model when the yield factor is low (i.e., $y_H \leq \underline{y}_H$). When the yield factor is high (i.e., $y_H \geq \overline{y}_H$), though the farmer exerts a high yield effort, the relative food loss is the same as in the base model as the total food loss and the total yield increase proportionally. When the yield factor is intermediate (i.e., $\underline{y}_H < y_H < \overline{y}_H$), the relative food loss is lower than in the base model. This is because the retailer pays a higher wholesale price than in the base model to induce a high yield effort as well as a higher cosmetic quality effort, thus lowering the relative food loss. However, the relative food loss increases in the yield factor for intermediate values because as the yield factor increases, the wholesale price—and consequently cosmetic quality effort—decreases.

Impact of Cosmetic Standard on Food Loss. We examine the effect of the cosmetic standard on food loss. We find that the observation from the base model that the food loss under a high cosmetic standard may be lower than that under a low standard continues to hold. The conditions for this to hold are identical to the base case for very low or high yield factors. Interestingly, for intermediate yield factors, the yield effort can either amplify or shrink the region where $l(1) < l(0)$: See panel (a) or panel (b) of Figure 7 at a low or high intermediate yield factor, respectively. (Full characterization of the results can be found in Online Appendix Proposition A.1.) In the case of low intermediate yield factor values, the retailer prefers a high yield effort under a high standard but not under a low standard. To achieve a high yield effort, however, the retailer must increase the wholesale price, which also leads to a higher cosmetic quality effort. This grows the region where $l(1) < l(0)$. For high intermediate yield factor values, the retailer prefers a high yield effort under both standards, though only under a low standard must the retailer increase the wholesale price to induce yield effort. This increases the farmer's cosmetic quality effort under the low standard and shrinks the region where $l(1) < l(0)$. The increased cosmetic quality effort under the low standard also means that for a low price premium, despite a zero rejection rate difference η, the relative food loss under the high standard strictly exceeds that under the low standard (see Panel (b) of Figure 7 the horizontal axis before it meets the thick dark line).

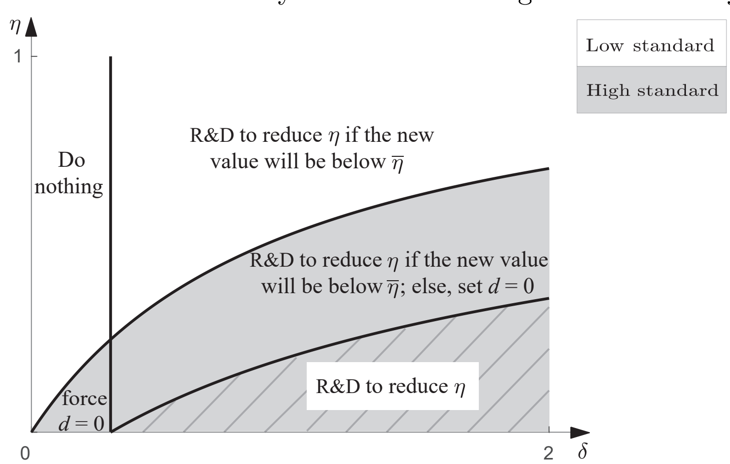
Figure 7: Compare relative food loss under both standards for intermediate yield factor values



(a) Low intermediate y_H (with $y_H = 2.2$) (b) High intermediate y_H (with $y_H = 4$)

Notes. In this example, $p = 7$, $c = 6$, $k = 0.8$, and $g_H = 0.4$.

Figure 8: Policy recommendations with yield effort for a high intermediate yield factor value



Notes. In this example, $p = 7$, $c = 6$, $k = 0.8$, and $y_H = 4$.

Lowering Food Loss: Policy Implications. In the presence of yield effort, the policy recommendations to reduce food loss in the base model continue to hold with the exception of high intermediate yield factors and very low price premium (see Figure 8). When the price premium is small and the rejection rate difference is high, none of the three policies mentioned in §5.3 can lower food loss. When the price premium is small and the rejection rate difference is low, investing

Table 2: Fruits and Vegetables: Processing Options

	Tomato	Cucumber	Strawberry	Broccoli	Apple
Processing option	Limited: separate supply chain for juicing and preserving	Limited except for minimally processed sliced market	Yes: juicing, freezing, preserving	Limited except for some freezing	Yes: juicing, minimal processing, preserving
Rejects used for human consumption	10%	25%	50%	0%	70%

-Data on processing options are from https://www.wifss.ucdavis.edu/materials/#produce-section1f117-335c for tomatoes, cucumbers, and strawberries and from https://extension.psu.edu/broccoli-production and https://extension.psu.edu/apple-production for broccoli and apples.
-Data on use of rejected produce for human consumption is from Gellynck et al. (2017).

in agricultural R&D is no longer the best approach to reduce relative food loss, and the lowest relative food loss is achieved by imposing a low cosmetic standard: When forced to adopt a low standard, the retailer sets a wholesale price higher than in the base model to induce the farmer's yield effort, which also increases the cosmetic quality effort and achieves the lowest relative food loss amongst all the three policy options mentioned.

6.2 Alternative sales channel

Produce below the cosmetic standard in the fresh market may be sold to an alternative sales channel that accepts less-than-perfect produce. We examine the impact of an alternative sales channel on the retailer and farmer interaction and on food loss. Such alternative channels include farmer's markets, cooperatives, or subscription boxes. Another example is the processing market, in which produce is frozen, canned, pureed, or processed as ready-to-eat food before being sold to end consumers, where the cosmetic standard is usually not a concern as the nature of processing often removes the end consumer's cosmetic preferences. Table 2 presents the processing options for the produce mentioned in Table 1. (Note while some produce, such as tomatoes, may be assumed to have abundant processing outlets, this is not the case as the processors operate with different supply chains and do not purchase from the same farmers as in the fresh market.) This table also shows that the proportion of yield rejected from the fresh market but still recovered for human consumption varies greatly, for instance, from 10% for tomatoes to 70% for apples. We assume that the alternative sales channel operates independently from the retailer.

We denote the percentage of the produce rejected for the fresh market but sold to the alternative channel by $\xi \in [0, 1]$. We assume there is no cosmetic standard in the alternative channel. We denote the unit wholesale price in the alternative channel by w_p, which is typically lower than that in the fresh market, w_f (e.g., USDA, Agricultural Marketing Service 2022), and thus we assume $w_p \leq w_f$. We also assume $c < w_p$ to avoid trivial cases in which the farmer does not sell to the alternative channel.

6.2.1 Characterize the farmer and retailer's optimal decisions

Farmer's optimal harvesting decision and effort level. In the presence of an alternative sales channel, at $t = 3$, we can easily show that given a cosmetic standard $d \in \{0, 1\}$, the farmer optimally harvests $(1 - \eta d)e$ to sell to the retailer at a price w_f and ξ proportion of the rest, i.e., $\xi(1-(1-\eta d)e)$, to the alternative channel at a price w_p. At $t = 2$, given the contract terms (d, w_f), the farmer determines the effort level to maximize the expected profit as follows:

$$\max_{e\in[0,1]} \left\{(w_f - c)(1 - \eta d)e + \xi(w_p - c)(1 - (1 - \eta d)e) - ke^2\right\},$$

where different from the base model, there is an additional second term, representing the profit of selling in the alternative channel. We characterize the farmer's optimal cosmetic quality effort in Online Appendix A.2.

Retailer's optimal contract decision. At $t = 1$, the retailer determines the contract terms (d, w_f) that maximize her expected profit. The retailer's profit expression has not changed, and we provide the optimal retailer decisions, taking into account the farmer's best response in future periods, in Online Appendix A.2. We characterize the equilibrium and compare the retailer's contract decisions to those in the base model in Proposition 6.

Proposition 6 *In the presence of an alternative sales channel, the equilibrium is the same as in the base model except c is replaced by $\bar{c} = c + (w_p - c)\xi$. Compared to the base model, the retailer sets a weakly higher cosmetic standard and a higher wholesale price.*

Proposition 6 shows that in the presence of an alternative selling outlet for the produce—even one who sets *no* cosmetic quality standard, the retailer is more demanding on cosmetic quality, but never less. This is to counteract the disincentive effect on the farmer's effort from selling non-conforming produce to the alternative channel. The retailer must pay a higher wholesale price compared to the base model, which pushes the retailer to set a higher cosmetic standard to receive the price premium from end consumers.

6.2.2 Impact of alternative sales channel on food loss

We examine the food loss at equilibrium in the presence of an alternative sales channel. In particular, we focus on how the food loss changes as the proportion that can be sold to the alternative channel, ξ, changes. We define food loss $L(d)$ as the difference between the total (normalized) yield and the harvest that is sold to either the fresh market or the alternative channel, i.e.,

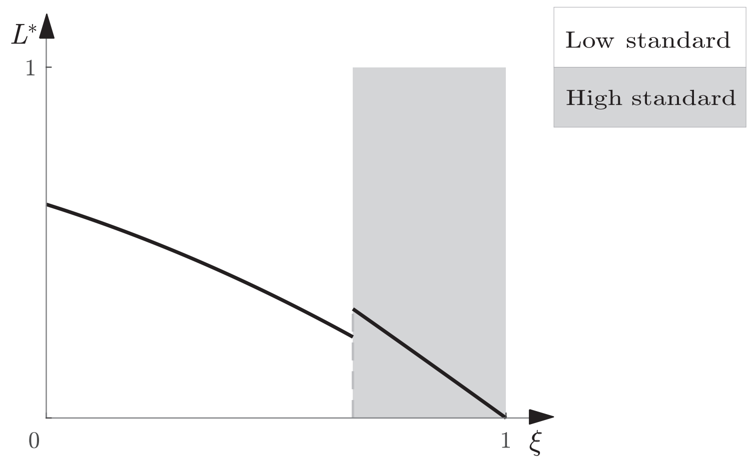
$$L(d) = 1 - (1 - \eta d)e^*(d, w_f^*(d)) - \xi(1 - (1 - \eta d)e^*(d, w_f^*(d))),$$

where the third term is the proportion sold to the alternative channel. Similar to the base model, we further denote the food loss at the equilibrium, i.e., $L(d^*) = L^*$.

As expected, the presence of an alternative sales channel reduces food loss compared to the base model: Though the cosmetic standard may increase, a portion of the produce, ξ, is absorbed by the alternative channel. However, this happens in a non-monotonic fashion as the absorption rate ξ increases. This behavior is formally characterized in Proposition 7.

Proposition 7 *In the presence of an alternative sales channel, if* $\hat{\eta} < \eta < \frac{\delta}{p+\delta-w_p}$, L^* *is non-monotonic in* ξ *with a jump at* $\frac{\eta(p+\delta-c)-\delta}{\eta(w_p-c)}$.

Figure 9: Impact of ξ on the food loss in the presence of an alternative sales channel



Notes. In this example, $p = 7, c = 6, k = 0.8$, $\delta = 1$, $w_p = 6.5$, and $\eta = 0.6$.

Figure 9 shows that for a *given* standard, the food loss decreases in the absorption rate, i.e., in either the grey or white region, L^* always decreases. However, a non-monotonic upward jump occurs when the retailer switches from a low to a high standard to counteract the farmer's incentive to lower his effort as he sells a higher percentage to the alternative channel. The resulting greater rejection rate due to a high standard outweighs the reduction in food loss from the higher absorption rate in the alternative channel, resulting in a net increase in the total food loss.

Impact of the cosmetic standard on food loss. We characterize the impact of the cosmetic standard on food loss in the presence of an alternative sales channel in Proposition 8.

Proposition 8 *In the presence of an alternative sales channel,* $L(1) < L(0)$ *when* $\eta < 1 - \sqrt{\frac{p-\bar{c}}{p+\delta-\bar{c}}}$, *where* $\bar{c} = c + (w_p - c)\xi$; *and* $L(1) \geq L(0)$ *otherwise.*

Proposition 8 shows that the results from the base model on the impact of the cosmetic standard continue to hold in this extension, i.e., the food loss under the high standard can be lower than that under the low standard, $L(1) < L(0)$. Furthermore, compared to the base model, the region where $L(1) < L(0)$ enlarges in the presence of an alternative sales channel because the alternative channel's ability to absorb a portion of the food loss reduces the impact of the high cosmetic standard on food loss.

Lowering food loss: Policy Implications. The presence of an alternative sales channel does not affect the existing policy recommendations qualitatively, and all our recommendations from the base case remain. However, policymakers may potentially have another arrow in their quiver if an intervention can be found that increases the absorption rate of the alternative channel. Nevertheless, this has to be calibrated carefully as an increase in the absorption may prompt the retailer to switch from a low standard to a high standard, which may increase food loss.

6.3 Harvesting cost variability

We next examine how the farmer and retailer interaction and associated food loss are affected by harvesting cost variability. Harvesting cost is highly uncertain because many produce is harvested manually to reduce the mechanization damage, and the harvesting labor mainly consists of seasonal workers, largely made up of immigrants (Calvin and Martin 2010). As a result, the harvesting labor cost highly depends on labor availability, which is affected by unexpected shocks such as the tightening of immigration policies. In case of a large shock, the harvesting cost could even exceed the wholesale price, where the farmer may not be able to harvest all the qualifying produce. For example, in 2017 in the U.S., newspaper headlines warned of a lack of (immigrant) labor, causing produce to rot in the fields (Economist 2017). According to Lee et al. (2017), about 6% of planted fruits and vegetable acreage in the U.S. alone was not harvested in 2011.

We model the harvesting cost as either high or low, with $c + \epsilon$ or $c - \epsilon$, respectively, where $\epsilon \in [0, c)$. The two cost outcomes occur with equal probability, so the mean harvesting cost is c, as in the base model. This harvesting cost uncertainty is realized after the farmer exerts cosmetic quality efforts but before determining the harvesting proportion. We further assume that $\epsilon \leq 3(p - c)$ so that for a given optimal cosmetic standard and a wholesale price less than the high harvesting cost, the expected food loss cannot be less than in the base case. We continue to assume the cosmetic quality effort is never at maximum in equilibrium, which corresponds to $4k > \max\left\{\frac{p+\delta-c+\epsilon}{2}, \frac{2(7+4\sqrt{2})(p+\delta-c)}{17}\right\}$. We modify the assumption $w_f \geq c$ from the base model to be $w_f \geq c - \epsilon$ so that it is optimal for the farmer to harvest at low cost.

6.3.1 Characterizing the farmer and retailer's optimal decisions

Farmer's optimal harvesting and effort decisions. At $t = 3$, given the contract terms (d, w_f) and realized harvesting cost (i.e., either $c+\epsilon$ or $c-\epsilon$), the farmer maximizes his expected profit by determining the optimal proportion of produce to harvest. Note that since $w_f \geq c - \epsilon$, the farmer optimally harvests all qualified produce if the realized cost is low at $c - \epsilon$. If the realized cost is high at $c+\epsilon$, it immediately follows that the farmer harvests all the qualified produce if $w_f \geq c+\epsilon$, and nothing otherwise. In other words, the farmer harvests under either only low cost or under both costs, which we label by L and B, respectively. At $t = 2$, given the contract terms (d, w_f) and the optimal harvesting decision under each cost realization, the farmer determines the optimal effort level to maximize the expected profit as follows:

$$\max_{e\in[0,1]} \frac{1}{2}\left[w_f - (c-\epsilon) + (w_f - (c+\epsilon))^+\right](1-\eta d)e - ke^2, \tag{6}$$

where $x^+ := \max\{x, 0\}$. Eq. (6) uses the *expected* profit margin $\frac{1}{2}\left[w_f - (c-\epsilon) + (w_f - (c+\epsilon))^+\right]$, where $(w_f - (c+\epsilon))^+$ equals zero if the wholesale price is lower than the high harvesting cost $c+\epsilon$. The optimal farmer effort level $e^*(d, w_f)$ is characterized in Online Appendix A.3.

Retailer's optimal contract decision. At $t = 1$, the retailer determines the cosmetic quality standard d and sets the wholesale price w_f to maximize her expected profit, anticipating the farmer's best-response harvesting and effort decisions at $t = 3$ and $t = 2$. As in the base model, we first determine the retailer's optimal wholesale price for a given $d \in \{0, 1\}$, which is written as follows:

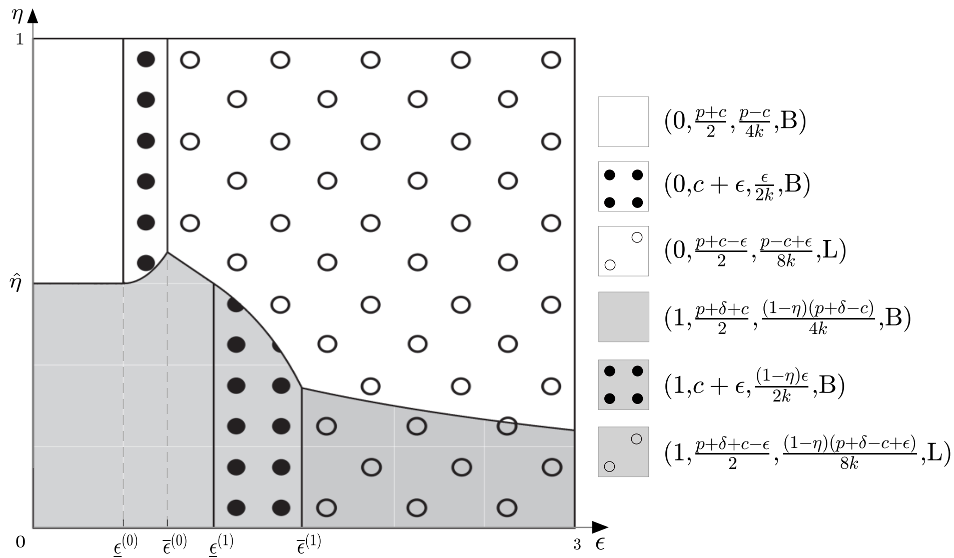
$$R(d) = \max_{w_f \geq c-\epsilon} (p + \delta d - w_f)\frac{\mathbf{I}\{w_f \geq c+\epsilon\} + 1}{2}(1-\eta d)e(d, w_f). \tag{7}$$

Eq (7) uses the *expected* profit margin $(p + \delta d - w_f)\frac{\mathbf{I}\{w_f \geq c+\epsilon\}+1}{2}$, where $\mathbf{I}\{\cdot\}$ is an indicator function which equals one if the condition inside the bracket holds and zero otherwise. In particular, it is the expected profit margin of the farmer harvesting under either both cost outcomes (if $w_f \geq c+\epsilon$) or only low cost. Finally, we determine the retailer's optimal standard using $d^* := \text{argmax}_{d\in\{0,1\}}\{R(d)\}$.

We denote the equilibrium as (d^*, w_f^*, e^*, L) and (d^*, w_f^*, e^*, B) for the case where the farmer harvests under only low cost and under both costs, respectively. Proposition 9 characterizes the equilibrium outcomes.

Proposition 9 *We characterize thresholds* $\underline{\epsilon}^{(0)} = \frac{p-c}{2}$, $\overline{\epsilon}^{(0)} = \frac{(7+4\sqrt{2})(p-c)}{17}$, $\underline{\epsilon}^{(1)} = \frac{p+\delta-c}{2}$, $\overline{\epsilon}^{(1)} = \frac{(7+4\sqrt{2})(p+\delta-c)}{17}$, *and a continuous, non-monotonic threshold function* $\tilde{\eta}(\epsilon)$ *such that the equilibrium is given as follows:*

Figure 10: Equilibrium outcome (d^*, w_f^*, e^*, L) or (d^*, w_f^*, e^*, B) under harvesting cost variability



Notes. In this example, we illustrate the case when $\overline{\epsilon}^{(0)} < \underline{\epsilon}^{(1)}$.

- $(0, \frac{p+c}{2}, \frac{p-c}{4k}, B)$ *for* $\epsilon < \underline{\epsilon}^{(0)}$ *and* $\eta > \tilde{\eta}(\epsilon)$
- $(1, \frac{p+\delta+c}{2}, \frac{(1-\eta)(p+\delta-c)}{4k}, B)$ *for* $\epsilon < \underline{\epsilon}^{(1)}$ *and* $\eta < \tilde{\eta}(\epsilon)$
- $(0, c+\epsilon, \frac{\epsilon}{2k}, B)$ *for* $\underline{\epsilon}^{(0)} < \epsilon < \overline{\epsilon}^{(0)}$ *and* $\eta > \tilde{\eta}(\epsilon)$
- $(1, c+\epsilon, \frac{(1-\eta)\epsilon}{2k}, B)$ *for* $\underline{\epsilon}^{(1)} < \epsilon < \overline{\epsilon}^{(1)}$ *and* $\eta < \tilde{\eta}(\epsilon)$
- $(0, \frac{p+c-\epsilon}{2}, \frac{p-c+\epsilon}{8k}, L)$ *for* $\epsilon > \overline{\epsilon}^{(0)}$ *and* $\eta > \tilde{\eta}(\epsilon)$
- $(1, \frac{p+\delta+c-\epsilon}{2}, \frac{(1-\eta)(p+\delta-c+\epsilon)}{8k}, L)$ *for* $\epsilon > \overline{\epsilon}^{(1)}$ *and* $\eta < \tilde{\eta}(\epsilon)$

The equilibrium characterized in Proposition 9 is indicated on the $\epsilon - \eta$ plane in Figure 10. When ϵ is small (i.e., $\epsilon < \underline{\epsilon}^{(d)}$ for $d \in \{0, 1\}$), the optimal wholesale price in the base case is sufficient to induce harvesting under both cost realizations. Therefore, the equilibrium is the same as that in the base model (see the top and bottom left regions in Figure 10). When ϵ is medium (i.e., $\underline{\epsilon}^{(d)} < \epsilon < \overline{\epsilon}^{(d)}$ for $d \in \{0, 1\}$), the optimal wholesale price in the base case is no longer sufficient to induce harvesting under both realizations, and the retailer optimally sets the wholesale price at $c + \epsilon$ to induce the farmer to harvest under both costs (see the top and bottom middle regions in Figure 10). This also induces the farmer to choose a higher effort level than the base case. When ϵ is large (i.e., $\epsilon > \overline{\epsilon}^{(d)}$ for $d \in \{0, 1\}$), the retailer prefers the farmer to harvest only under the low cost outcome. As the low harvesting cost decreases in the variability, the retailer's optimal wholesale price is lower than that in the base case and decreases in the cost variability (see the top and bottom right regions in Figure 10).

See on Figure 10 the curve that separates the white (low standard) region and the grey (high standard) region, which represents the threshold below which the retailer sets a high standard. When cost variability increases, this curve is non-monotonic, which implies that the impact of cost variability on this threshold is non-monotonic. In particular, the threshold is non-decreasing in the cost variability for $\epsilon < \bar{\epsilon}^{(0)}$ and decreasing thereafter.

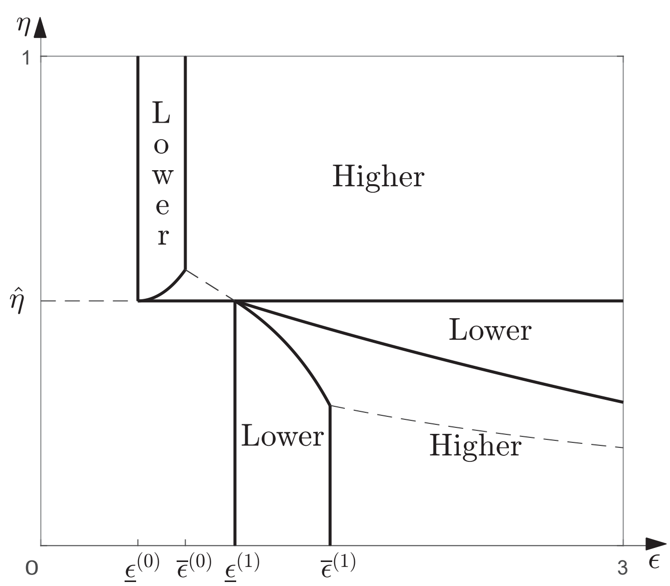
6.3.2 Impact of harvesting cost variability on food loss.

We next consider the effect of harvesting cost variability on food loss. We define the expected food loss given d as follows:

$$L(d) = 1 - (1 - \eta d) e^*(d, w_f^*(d)) \frac{1}{2} \left[\mathbf{I}\{w_f^*(d) \geq c + \epsilon\} + 1 \right]. \tag{8}$$

Eq (8) uses the expected proportion of produce that is harvested, which depends on $w_f^*(d)$: If $w_f^*(d) \geq c + \epsilon$, the farmer harvests under both costs; otherwise, the farmer harvests only under the low cost. Similar to the base model, we define L^* as the food loss at equilibrium, i.e., $L^* = L(d^*)$. We fully characterize the food loss for different values of ϵ in Online Appendix A.3.

Figure 11: Effect of cost variability on food loss compared to the base model



Notes. In this example, we have $\bar{\epsilon}^{(0)} < \underline{\epsilon}^{(1)}$. In regions labeled "Lower" ("Higher"), the food loss in the presence of harvesting cost variability is lower (higher) than that in the base model. In regions without labels, the food loss is the same as in the base model.

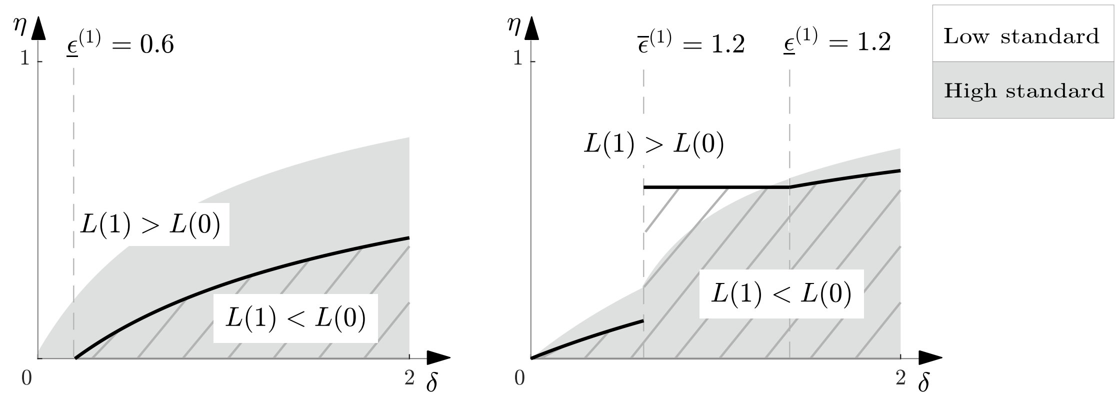
We compare food loss in the presence of cost variability to that in the base model in Figure 11.

As seen, the impact of harvesting cost variability on food loss is non-monotonic. If the harvesting variability ϵ is small (i.e., $\epsilon \leq \underline{\epsilon}^{(d)}$ for $d \in \{0, 1\}$), the cosmetic standard and food loss are the same as that in the base model. If ϵ is intermediate (i.e., $\underline{\epsilon}^{(d)} < \epsilon < \overline{\epsilon}^{(d)}$ for $d \in \{0, 1\}$), the food loss is less than in the base model because the retailer offers a higher wholesale price to induce harvesting under a high cost, which increases the farmer's cosmetic quality effort. If ϵ is high (i.e., $\epsilon \geq \underline{\epsilon}^{(d)}$ for $d \in \{0, 1\}$), we consider two cases based on the rejection rate difference η. When the retailer sets the low standard in the base model ($\eta > \hat{\eta}$), a high ϵ causes the retailer to either increase the standard to justify the higher wholesale price or forgo harvesting under a high cost realization, either of which raises the food loss above the level in the base model. When the retailer sets the high standard in equilibrium in the base model (i.e., $\eta < \hat{\eta}$), a high ϵ causes the food loss to increase at first because the farmer only harvests under a low cost realization. However, the retailer may also optimally switch from the high standard in the base model to the low standard in this extended model. This may lower the expected food loss if the reduced incidence of rejection outweighs the increase from only harvesting under a low cost. Therefore, high harvesting cost variability can lower food loss compared to the base model for a low rejection rate difference.

Impact of the cosmetic standard on food loss. Similar to the base model, we also compare the food loss under a high or a low cosmetic standard. We find that the insights from the base model continue to hold when cost variability is very low or very high. That is, the food loss under a high standard can be lower than that under a low standard. In addition, we also observe the following interesting results for intermediate levels of cost variability, which are illustrated in Panels (a) and (b) in Figure 12. Similar to the extension with yield effort (see §6.1), Panel (a) shows that in the presence of cost variability, food loss under a high standard can be higher than under a low standard despite a zero rejection rate difference. This happens because the retailer increases the wholesale price under a low standard—yet not under a high standard—to encourage harvesting under both costs, which increases the farmer's effort. Panel (b) shows a novel result: When the retailer chooses a low standard in equilibrium, food loss under a high standard can be lower than that under a low standard (see on Panel (b) the striped region on white background). This is because, under a high standard, the farmer harvests under both cost realizations while harvesting under only the low cost at a low standard, which lowers the food loss more than the increase of food loss from a high standard.

Lowering food loss: Policy implications. While extreme values of cost variability—very low or very large—do not alter the optimal policy recommendations qualitatively compared to the base model, there is a significant change for intermediate cost variability parameters (i.e., $\epsilon \in [\overline{\epsilon}^{(0)}, \overline{\epsilon}^{(1)}]$).

Figure 12: Food loss under high or low cosmetic standard with harvesting cost variability



(a) Low intermediate ϵ (with $\epsilon = 0.6$) (b) High intermediate ϵ (with $\epsilon = 1.2$)

Notes. In this example, $p = 7$, $c = 6$, and $k = 0.8$. Moreover, $\underline{\epsilon}^{(0)} = 0.5$ and $\overline{\epsilon}^{(0)} = 0.74$.

Focusing on Panel (b) of Figure 12, we observe that for a high intermediate cost variability, if the rejection rate difference and price premium are intermediate, the policymaker may lower the food loss by forcing the retailer to set a *high* cosmetic standard. This counterintuitive policy recommendation is because, in these regions, the retailer optimally chooses a low standard and a low wholesale price; thus, the farmer harvests under only low cost. Forcing the retailer to choose a high standard causes the retailer to increase the wholesale price and thus incentivizes the farmer to harvest under both cost realizations, which lowers the food loss.

7. Managerial insights and conclusion

As a significant amount of food loss has been linked to the high cosmetic standards set by retailers, we study this food loss in upstream of the agricultural supply chain at the farm level by examining a retailer's interaction with a farmer. In particular, we capture the tradeoff of the retailer's cosmetic standard decision: A high standard allows the retailer to sell produce to end-consumers with a price premium but reduces the proportion of the produce that satisfies this standard. We examine this in the context of contract farming, where the retailer offers a contract to the farmer specifying both the cosmetic standard and the wholesale price in a Stackelberg game. Given the contract terms, the farmer decides her costly effort, which affects the proportion of produce satisfying the cosmetic standard.

Our paper is among the very few papers that investigate upstream food loss at the farm level. Within this stream of research, our paper is the only one that explores the economic incentives of the retailer to adopt high cosmetic standards via the interaction with the farmer and shows their impact on food loss. Our analysis yields actionable policy recommendations to reduce food loss, which continue to hold in multiple extensions.

We lift the veil on the role of the retailer's high cosmetic standards as a cause of food loss at the farmer level. We show that compared to setting a low standard, the retailer setting a high standard may not necessarily lead to a higher food loss and may lower food loss instead. This happens when the price premium is sufficiently high to induce a farmer's effort that compensates for the increased rejection rate due to a high standard. In other words, though a high standard may lead to significant food loss, it is not necessarily true that a high standard means a higher food loss than a low standard.

More importantly, based on our results, we assess the effectiveness of three possible policy interventions in reducing food loss and offer our final recommendations.

(1) *A ban on high cosmetic standards*: As high standards have been linked to high food loss, it was naturally assumed that banning such high standards and enforcing low standards may lower food loss. However, we caution the policymakers to use this policy carefully, as it may backfire and increase food loss instead. Specifically, this happens when the price premium is high and the relative difference between the rejection rates under both standards is low. This policy should only be implemented for intermediate price premiums and relative differences. Furthermore, our model shows that scrapping mandatory standard regulation, as was done in the E.U. in 2009, may not reduce cosmetic standards in the market. Due to economic incentives, retailers may set their own high standards, which may be even higher than the government standards (Mattsson 2014).

(2) *Reducing the price premium for high cosmetic standards by education campaigns:* For example, a growing movement advocates for the inclusion of less-than-perfect food in supermarkets by educating consumers to reduce their preference for aesthetically pleasing produce. The idea is to reduce the price premium for high cosmetic quality, which may, in turn, induce retailers to lower their cosmetic standards. We caution against this intervention, as it may increase food loss: It is only effective at reducing food loss if the decrease of the premium is so large that it incentivizes the retailer to switch to a low standard when the price premium and rejection rate difference are intermediate. For small decreases in the price premium, the retailer continues to set a high standard but decreases the wholesale price, which decreases the farmer's effort and thus increases food loss.

(3) *Reducing the rejection rate under the high standard by investment in agricultural research and development (R&D):* This is a less interventionist approach compared to the previous two. Such policy interventions always reduce food loss whenever the retailer sets a high cosmetic standard. Nevertheless, the optimality of R&D compared with a ban on cosmetic quality standards depends

on the rejection rate difference achieved after R&D investment. If this difference can be reduced below a minimum threshold, the new food loss will be less than what the ban on cosmetic standards can achieve; whereas if this difference remains above that minimum threshold, a ban on cosmetic standards would have achieved a lower food loss than R&D.

To summarize, policies that reduce the price premium are never a preferred option, and we recommend either banning a high standard or reducing the rejection rate at a high standard, depending on the relative rejection rate difference and the price premium. If the difference is very low or the price premium very high, the only intervention that can reduce food loss is decreasing the rejection rate under the high standard by R&D. For intermediate rejection rate difference and price premium, the recommended policy intervention is to reduce the rejection rate at a high standard by R&D to be below a threshold. If such a reduction cannot be achieved, it is more effective to force the retailer to set a low standard. If the difference is high and the price premium is low, the only effective policy is reducing the rejection rate under a high standard by a large amount through R&D to bring the difference below a threshold. All these policy insights continue to hold when we endogenize the retail price.

We also extend our base model to consider three salient features of the produce market: the presence of a yield-enhancing effort, an alternative sales channel, or harvesting cost variability. We show that our results and policy recommendations continue to hold with additional insights. For instance, in the presence of yield effort, imposing a ban on high cosmetic standards may become the sole viable option to reduce food loss in some circumstances. In the presence of harvesting cost variability, there exists a range of intermediate cost variability values where the policy intervention resulting in the lowest food loss is forcing the retailer to set a high standard.

Relaxing some assumptions in our paper should provide fruitful research directions. First, one can use more complex contract forms, for instance, an option contract proposed for a produce supply chain where the retailer is given options to buy produce at a fixed price when demand information is realized. Second, we consider the food loss upstream and acknowledge that food waste also occurs downstream, at the retailer and end consumers, which can also be interesting to examine. Lastly, one can consider competition between supply chains and more complex supply networks with multiple farmers.

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Online Appendix for *Impact of Cosmetic Standards on Food Loss*

A. Additional results

A.1 Extension with yield-enhancing efforts

Lemma A.1 *In the presence of yield effort, the farmer's optimal decisions are as follows:*

- *If* $y_H > 1 + \frac{g_H}{k}$, *we have*

$$(e^*(d,w_f), a^*(d,w_f)) = \begin{cases} (\frac{(1-\eta d)(w_f-c)}{2k}, 0) & \text{if } k > \frac{(y_H-1)(1-\eta d)^2(w_f-c)^2}{4g_H} \\ (\frac{(1-\eta d)(w_f-c)}{2k}, 1) & \text{if } \frac{(1-\eta d)(w_f-c)}{2} < k \le \frac{(y_H-1)(1-\eta d)^2(w_f-c)^2}{4g_H} \\ (1,1) & \text{if } k \le \frac{(1-\eta d)(w_f-c)}{2} \end{cases}$$

- *If* $y_H \le 1 + \frac{g_H}{k}$, *we have*

$$(e^*(d,w_f), a^*(d,w_f)) = \begin{cases} (\frac{(1-\eta d)(w_f-c)}{2k}, 0) & \text{if } k > \frac{(1-\eta d)(w_f-c)}{2} \\ (1,0) & \text{if } (1-\eta d)(w_f-c) - \frac{g_H}{y_H-1} < k \le \frac{(1-\eta d)(w_f-c)}{2} \\ (1,1) & \text{if } k \le (1-\eta d)(w_f-c) - \frac{g_H}{y_H-1} \end{cases}$$

Lemma A.2 *In the presence of yield-enhancing effort,* l^* *is given as follows:*

- *When* $\eta > \hat{\eta}$, l^* *is as follows:*

$$l^* = \begin{cases} 1 - \frac{p-c}{4k} & \text{if } 1 \le y_H \le \underline{y}_H \\ 1 - \sqrt{\frac{g_H}{k(y_H-1)}} & \text{if } \underline{y}_H < y_H < \overline{y}_H \\ 1 - \frac{p-c}{4k} & \text{if } y_H \ge \overline{y}_H \end{cases}$$

- *When* $\eta \le \hat{\eta}$, l^* *is as follows:*

$$l^* = \begin{cases} 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k} & \text{if } 1 \le y_H \le \underline{y}_H \\ 1 - (1-\eta)\sqrt{\frac{g_H}{k(y_H-1)}} & \text{if } \underline{y}_H < y_H < \overline{y}_H \\ 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k} & \text{if } y_H \ge \overline{y}_H \end{cases}$$

Proposition A.1 *In the model with yield-enhancing effort,*

- *For* $1 \le y_H \le \underline{y}_H^{(1)}$ *or* $y_H \ge \overline{y}_H^{(0)}$, $l(1) < l(0)$ *when* $\eta < \overline{\eta}$ *and* $l(1) \ge l(0)$ *otherwise.*

- *For* $\underline{y}_H^{(1)} < y_H \le \min\{\overline{y}_H^{(1)}, \underline{y}_H^{(0)}\}$, $l(1) < l(0)$ *when* $\eta < \min\{\overline{\eta}, 1 - \sqrt{\frac{(y_H-1)(p-c)^2}{16kg_H}}\}$; *and* $l(1) \ge l(0)$ *otherwise.*

- *For* $\min\{\overline{y}_H^{(1)}, \underline{y}_H^{(0)}\} < y_H \le \max\{\overline{y}_H^{(1)}, \underline{y}_H^{(0)}\}$, *we have two cases:*
  (i) If $\delta > \frac{(p-c)(1-(y_H-\sqrt{y_H(y_H-1)}))}{y_H-\sqrt{y_H(y_H-1)}}$, $l(1) < l(0)$ *when* $\eta < \min\{\overline{\eta}, 1 - \sqrt{\frac{(y_H-1)(p-c)^2}{16kg_H}}\}$; *and* $l(1) \ge l(0)$ *otherwise. (ii)* $\delta \le \frac{(p-c)(1-(y_H-\sqrt{y_H(y_H-1)}))}{y_H-\sqrt{y_H(y_H-1)}}$, $l(1) \ge l(0)$ *always holds.*

- *For* $\max\{\overline{y}_H^{(1)}, \underline{y}_H^{(0)}\} < y_H \le \overline{y}_H^{(0)}$, $l(1) < l(0)$ *when* $\eta < 1 - \sqrt[4]{\frac{16kg_H}{(y_H-1)(p+\delta-c)^2}}$; *and* $l(1) \ge l(0)$ *otherwise.*

A.2 Extension with alternative sales channel

Lemma A.3 *In the presence of an alternative sales channel, the farmer's optimal effort is* $e^*(d, w_f) = \frac{(1-\eta d)((w_f-c)-(w_p-c)\xi)}{2k}$ *if* $k > \frac{1}{2}(1-\eta d)((w_f - c) - (w_p - c)\xi)$ *and* $e^*(d, w_f) = 1$ *otherwise.*

A.3 Extension with harvesting cost variability

Lemma A.4 *In the presence of harvesting cost variability, the farmer's optimal effort* $e^*(d, w_f) = \frac{(1-\eta d)(w_f-(c-\epsilon)+(w_f-(c+\epsilon))^+)}{4k}$ *if* $w_f \le \min\{c + \frac{2k}{1-\eta d}, c - \epsilon + \frac{4k}{1-\eta d}\}$ *and equals 1 otherwise.*

Proposition A.2 *In the presence of harvest cost variability, the food loss is as follows:*

- *When* $\eta > \tilde{\eta}(\epsilon)$, L^* *is as follows:*

$$L^* = \begin{cases} 1 - \frac{p-c}{4k} & \text{if } 0 \le \epsilon \le \underline{\epsilon}^{(0)} \\ 1 - \frac{\epsilon}{2k} & \text{if } \underline{\epsilon}^{(0)} < \epsilon \le \overline{\epsilon}^{(0)} \\ 1 - \frac{p-c+\epsilon}{16k} & \text{if } \epsilon > \overline{\epsilon}^{(0)} \end{cases}$$

- *When* $\eta < \tilde{\eta}(\epsilon)$, L^* *is as follows:*

$$L^* = \begin{cases} 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k} & \text{if } 0 \le \epsilon \le \underline{\epsilon}^{(1)} \\ 1 - \frac{(1-\eta)^2\epsilon}{2k)} & \text{if } \underline{\epsilon}^{(1)} < \epsilon \le \overline{\epsilon}^{(1)} \\ 1 - \frac{(1-\eta)^2(p+\delta-c+\epsilon)}{16k} & \text{if } \epsilon > \overline{\epsilon}^{(1)} \end{cases}$$

Proposition A.3 *The impact of cosmetic standard on the food loss considering harvest cost variability is as follows:*

- *For* $0 \le \epsilon \le \underline{\epsilon}^{(0)}$, *the result is identical to the base model.*
- *For* $\underline{\epsilon}^{(0)} < \epsilon \le min\{\overline{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\}$, $L(1) < L(0)$ *when* $\eta < 1 - \sqrt{\frac{2\epsilon}{p+\delta-c}}$; *and* $L(1) \ge L(0)$ *otherwise.*
- *For* $min\{\overline{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\} < \epsilon \le max\{\overline{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\}$, *if* $0 < \delta \le \frac{(8\sqrt{2}-3)(p-c)}{17}$, $L(1) \ge L(0)$ *always holds; If* $\delta > \frac{(8\sqrt{2}-3)(p-c)}{17}$, $L(1) < L(0)$ *when* $\eta < 1 - \sqrt{\frac{p-c+\epsilon}{4(p+\delta-c)}}$; *and* $L(1) \ge L(0)$ *otherwise.*
- *For* $max\{\overline{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\} < \epsilon \le \overline{\epsilon}^{(1)}$, $L(1) < L(0)$ *when* $\eta < 1 - \sqrt{\frac{p-c+\epsilon}{8\epsilon}}$; *and* $L(1) \ge L(0)$ *otherwise.*
- *For* $\overline{\epsilon}^{(1)} < \epsilon \le 3(p - c)$, $L(1) < L(0)$ *when* $\eta < 1 - \sqrt{\frac{p-c+\epsilon}{p+\delta-c+\epsilon}}$; *and* $L(1) \ge L(0)$ *otherwise.*

A.4 Proofs of additional results in Online Appendix A

Proof of Lemma A.1: We can rewrite Eq. (4) as follows:

$$\max_{a\in\{0,1\}} \left\{ (ay_H + 1 - a) \max_{e\in[0,1]} \{((w_f - c)(1 - \eta d)e - ke^2)\} - ag_H \right\}.$$

From Lemma 1, we know given a, we have $e^*(d, w_f) = \frac{(1-\eta d)(w_f-c)}{2k}$ if $c \le w_f < \frac{2k}{1-\eta d} + c$ and $e^* = 1$ for $w_f \ge \frac{2k}{1-\eta d} + c$. We substitute $e^*(d, w_f)$ into the farmer's profit expression given a and obtain

$$W(a) = \begin{cases} (ay_H + 1 - a)\frac{(1-\eta d)^2(w_f-c)^2}{4k} - ag_H & \text{if } c \le w_f < \frac{2k}{1-\eta d} + c \\ (ay_H + 1 - a)((1 - \eta d)(w_f - c) - k) - ag_H & \text{if } w_f \ge \frac{2k}{1-\eta d} + c \end{cases}$$

Then, the farmer's optimal profit is $\max\{W(0), W(1)\}$. For notational simplicity, we define $\bar{w}_f(d) := \sqrt{\frac{4kg_H}{y_H-1}}\frac{1}{1-\eta d} + c$. We consider the following two cases:

- For $c \leq w_f < \frac{2k}{1-\eta d} + c$: we can show that $W(1) > W(0)$ iff $w_f > \bar{w}_f(d)$; otherwise, $W(1) \leq W(0)$. We consider the following two subcases:
  - If $y_H \leq 1 + \frac{g_H}{k}$: as $\bar{w}_f(d) \geq \frac{2k}{1-\eta d} + c$, so $a^* = 0$ for $w_f \in \left[c, \frac{2k}{1-\eta d} + c\right]$.
  - If $y_H > 1 + \frac{g_H}{k}$: as $\bar{w}_f(d) < \frac{2k}{1-\eta d} + c$, so $a^* = 0$ for $w_f \in [c, \bar{w}_f(d)]$ and $a^* = 1$ for $w_f \in \left(\bar{w}_f(d), \frac{2k}{1-\eta d} + c\right)$.
- For $w_f \geq \frac{2k}{1-\eta d} + c$: we can show that $W(1) > W(0)$ iff $w_f > \frac{g_H+k(y_H-1)}{(1-\eta d)(y_H-1)} + c$; otherwise, $W(1) \leq W(0)$. We consider the following two subcases:
  - If $y_H \leq 1+\frac{g_H}{k}$: as $\frac{g_H+k(y_H-1)}{(1-\eta d)(y_H-1)}+c \geq \frac{2k}{1-\eta d}+c$, so $a^* = 0$ for $w_f \in \left[\frac{2k}{1-\eta d} + c, \frac{g_H+k(y_H-1)}{(1-\eta d)(y_H-1)} + c\right)$, and $a^* = 1$ for $w_f \geq \frac{g_H+k(y_H-1)}{(1-\eta d)(y_H-1)} + c$.
  - If $y_H > 1 + \frac{g_H}{k}$: as $\frac{g_H+k(y_H-1)}{(1-\eta d)(y_H-1)} + c < \frac{2k}{1-\eta d} + c$, so $a^* = 1$ for $w_f \geq \frac{2k}{1-\eta d} + c$.

We combine the results for e^* and a^* to obtain Lemma A.1.

Proof of Lemma A.2: Substituting d^*, e^*, and a^* from Proposition 4 into l^* gives Lemma A.2.

Proof of Proposition A.1: Recalling from the proof of Proposition 4, we define $\underline{y}_H^{(d)}$ as the positive solution to $\eta_1(d) = 0$, and $\overline{y}_H^{(d)} = 1 + \frac{16kg_H}{(p+\delta d-c)^2}$ as the solution to $\eta_2(d) = 0$. In addition, as shown in the proof of Proposition 4, $\overline{y}_H^{(d)} > \underline{y}_H^{(d)}$, $\overline{y}_H^{(1)} < \overline{y}_H^{(0)}$, and $\underline{y}_H^{(1)} < \underline{y}_H^{(0)}$. Furthermore, if $\delta > \frac{(p-c)(1-(y_H-\sqrt{y_H(y_H-1)}))}{y_H-\sqrt{y_H(y_H-1)}}$, $\overline{y}_H^{(1)} < \underline{y}_H^{(0)}$; otherwise, $\overline{y}_H^{(1)} \geq \underline{y}_H^{(0)}$. Next, we compare $l(0)$ with $l(1)$ in the following cases.

- When $1 \leq y_H \leq \underline{y}_H^{(1)}$ or $y_H \geq \overline{y}_H^{(0)}$, similar to the proof of Proposition 3, we can show $l(1) < l(0)$ when $\eta < \overline{\eta}$, and $l(1) \geq l(0)$ otherwise.
- When $\underline{y}_H^{(1)} < y_H \leq \min\{\overline{y}_H^{(1)}, \underline{y}_H^{(0)}\}$, we have $l(0) = 1 - \frac{p-c}{4k}$ and $l(1) = 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k}$ if $y_H \leq \underline{y}_H$ and $l(1) = 1 - (1-\eta)\sqrt{\frac{g_H}{k(y_H-1)}}$ if $y_H > \underline{y}_H$. Comparing $l(1)$ and $l(0)$, we have $l(1) < l(0)$ when $\eta < \min\{\overline{\eta}, 1 - \sqrt{\frac{(y_H-1)(p-c)^2}{16kg_H}}\}$.
- When $\min\{\overline{y}_H^{(1)}, \underline{y}_H^{(0)}\} < y_H \leq \max\{\overline{y}_H^{(1)}, \underline{y}_H^{(0)}\}$, we consider the following two cases:

  (i) If $\delta > \frac{(p-c)(1-(y_H-\sqrt{y_H(y_H-1)}))}{y_H-\sqrt{y_H(y_H-1)}}$, we have $\overline{y}_H^{(1)} < \underline{y}_H^{(0)}$. Then $l(0) = 1 - \frac{p-c}{4k}$ and

$$l(1) = \begin{cases} 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k} & \text{if } \underline{y}_H^{(1)} \leq y_H \leq \underline{y}_H \\ 1 - (1-\eta)\sqrt{\frac{g_H}{k(y_H-1)}} & \text{if } \underline{y}_H < y_H < \overline{y}_H \\ 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k} & \text{if } \overline{y}_H \leq y_H < \underline{y}_H^{(0)} \end{cases}$$

  Comparing $l(1)$ and $l(0)$, we have $l(1) < l(0)$ when $\eta < \min\{\overline{\eta}, 1 - \sqrt{\frac{(y_H-1)(p-c)^2}{16kg_H}}\}$.

  (ii) If $\delta \leq \frac{(p-c)(1-(y_H-\sqrt{y_H(y_H-1)}))}{y_H-\sqrt{y_H(y_H-1)}}$, we have $\overline{y}_H^{(1)} \geq \underline{y}_H^{(0)}$. Then $l(0) = 1 - \sqrt{\frac{g_H}{k(y_H-1)}}$ and $l(1) = 1 - (1-\eta)\sqrt{\frac{g_H}{k(y_H-1)}}$. Thus, $l(1) \geq l(0)$ always holds.

- When $\max\{\overline{y}_H^{(1)}, \underline{y}_H^{(0)}\} < y_H \leq \overline{y}_H^{(0)}$, we have $l(0) = 1 - \sqrt{\frac{g_H}{k(y_H-1)}}$. When $\max\{\overline{y}_H^{(1)}, \underline{y}_H^{(0)}\} < y_H \leq \overline{y}_H$, $l(1) = 1 - (1-\eta)\sqrt{\frac{g_H}{k(y_H-1)}}$, we always have $l(1) > l(0)$. When $\overline{y}_H < y_H \leq \overline{y}_H^{(0)}$, $l(1) = 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k}$, we have $l(1) < l(0)$ when $\eta < 1 - \sqrt[4]{\frac{16kg_H}{(y_H-1)(p+\delta-c)}}$.

Proof of Lemma A.3: We denote $\overline{c} = c + \xi(w_p - c)$. We can rewrite the farmer's optimal effort decision in §6.2 as $\max_{e\in[0,1]} \left\{(w_f - \overline{c})(1-\eta d)e - ke^2 + \xi(w_p - c)\right\}$. The proof is identical to that of Lemma 1 except replacing c with $\overline{c}$.

Proof of Lemma A.4: Given (d, w_f), we derive the farmer's optimal effort in the following:

(i) When $c - \epsilon \leq w_f < c + \epsilon$, the farmer only harvests under low harvesting cost $c - \epsilon$ and his objective function is $\frac{(1-\eta d)e}{2}(w_f - c + \epsilon) - ke^2$, thus the solution to the unconstrained first-order condition is $e = \frac{(1-\eta d)(w_f - c+\epsilon)}{4k}$. Then the optimal effort is:

$$e^*(d, w_f) = \begin{cases} \frac{(1-\eta d)(w_f - c+\epsilon)}{4k} & \text{if } c - \epsilon \leq w_f < \min\{c+\epsilon, \frac{4k}{1-\eta d} + c - \epsilon\} \\ 1 & \text{if } \min\{c+\epsilon, \frac{4k}{1-\eta d} + c - \epsilon\} < w_f < c + \epsilon. \end{cases}$$

(ii) When $w_f \geq c+\epsilon$, the farmer harvests under both costs and his objective function is simplified to $\frac{(1-\eta d)e}{2}(w_f - c) - ke^2$. The solution to the unconstrained first-order condition is $e = \frac{(1-\eta d)(w_f - c)}{2k}$. Hence, the optimal effort level is:

$$e^*(d, w_f) = \begin{cases} \frac{(1-\eta d)(w_f - c)}{2k} & \text{if } c + \epsilon < w_f < \frac{2k}{1-\eta d} + c \\ 1 & \text{if } w_f \geq \max\{c + \epsilon, \frac{2k}{1-\eta d} + c\} \end{cases}$$

Therefore, we can find the optimal farmer effort as follows:

- If $\epsilon > \frac{2k}{1-\eta d}$, then $c - \epsilon < \frac{4k}{1-\eta d} + c - \epsilon < c + \frac{2k}{1-\eta d} < c + \epsilon$, so we have:

$$e^*(d, w_f) = \begin{cases} \frac{(1-\eta d)(w_f - c+\epsilon)}{4k} & \text{if } c - \epsilon \leq w_f \leq \frac{4k}{1-\eta d} + c - \epsilon \text{ (Harvesting under only low cost)} \\ 1 & \text{if } \frac{4k}{1-\eta d} + c - \epsilon < w_f < c + \epsilon \text{ (Harvesting under only low cost)} \\ 1 & \text{if } w_f \geq c + \epsilon \text{ (Harvesting under both costs)} \end{cases}$$

- If $0 \leq \epsilon \leq \frac{2k}{1-\eta d}$, then $c - \epsilon < c + \epsilon \leq c + \frac{2k}{1-\eta d} \leq \frac{4k}{1-\eta d} + c - \epsilon$, so we have

$$e^*(d, w_f) = \begin{cases} \frac{(1-\eta d)(w_f - c+\epsilon)}{4k} & \text{if } c - \epsilon \leq w_f < c + \epsilon \text{ (Harvesting under only low cost)} \\ \frac{(1-\eta d)(w_f - c)}{2k} & \text{if } c + \epsilon \leq w_f \leq \frac{2k}{1-\eta d} + c \text{ (Harvesting under both costs)} \\ 1, & \text{if } w_f > \frac{2k}{1-\eta d} + c \text{ (Harvesting under both costs)} \end{cases}$$

Combining these two cases, we can characterize the optimal farmer's effort shown in this lemma.

Proof of Proposition A.2: This follows by substituting the equilibrium decisions defined in Proposition 9 into the expression of food loss.

Proof of Proposition A.3: In the presence of harvesting cost variability, we have:

- When $\epsilon \leq \underline{\epsilon}^{(0)}$, $L(1) < L(0)$ when $\eta < \overline{\eta}$; $L(1) \geq L(0)$ otherwise.

- When $\underline{\epsilon}^{(0)} < \epsilon \leq \min\{\overline{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\}$, we have $L(0) = 1 - \frac{\epsilon}{2k}$ and $L(1) = 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k}$. $L(1) < L(0)$ when $\eta < 1 - \sqrt{\frac{2\epsilon}{p+\delta-c}}$; and $L(1) \geq L(0)$ otherwise.

- When $\min\{\bar{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\} < \epsilon \le \max\{\bar{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\}$, (i) If $0 < \delta \le \frac{(8\sqrt{2}-3)(p-c)}{17}$, we have $L(0) = 1 - \frac{\epsilon}{2k}$ and $L(1) = 1 - \frac{\epsilon(1-\eta)^2}{2k}$. Thus, $L(1) \ge L(0)$ always holds; (ii) If $\delta > \frac{(8\sqrt{2}-3)(p-c)}{17}$, we have $L(0) = 1 - \frac{p-c+\epsilon}{16k}$ and $L(1) = 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k}$. Thus, $L(1) < L(0)$ when $\eta < 1 - \sqrt{\frac{p-c+\epsilon}{4(p+\delta-c)}}$; and $L(1) \ge L(0)$ otherwise.
- When $\max\{\bar{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\} < \epsilon \le \bar{\epsilon}^{(1)}$, we have $L(0) = 1 - \frac{p-c+\epsilon}{16k}$ and $L(1) = 1 - \frac{\epsilon(1-\eta)^2}{2k}$. Thus, $L(1) < L(0)$ when $\eta < 1 - \sqrt{\frac{p-c+\epsilon}{8\epsilon}}$; and $L(1) \ge L(0)$ otherwise.
- When $\bar{\epsilon}^{(1)} < \epsilon \le 3(p-c)$, we have $L(0) = 1 - \frac{p-c+\epsilon}{16k}$ and $L(1) = 1 - \frac{(1-\eta)^2(p+\delta-c+\epsilon)}{16k}$. Thus, $L(1) < L(0)$ when $\eta < 1 - \sqrt{\frac{p-c+\epsilon}{p+\delta-c+\epsilon}}$; and $L(1) \ge L(0)$ otherwise.

B. Proofs of results in the main text

Proof of Lemma 1: In Eq. (1), as the objective function $(w_f - c)(1-\eta d)e - ke^2$ is concave in e, the solution to the first-order condition $(1-\eta d)(w_f - c) - 2ke = 0$ is optimal when $\frac{(1-\eta d)(w_f-c)}{2k} < 1$ (note that $\frac{(1-\eta d)(w_f-c)}{2k} \ge 0$ as $w_f \ge c$), i.e., in this case, $e^*(d, w_f) = \frac{(1-\eta d)(w_f-c)}{2k}$. Otherwise, $e^*(d, w_f) = 1$.

Proof of Proposition 1: From $0 \le \eta < 1$, $w_f \ge c$, and $k > 0$, we have the farmer's optimal profits is at least zero. Substituting the farmer's optimal effort level from Lemma 1 into the retailer's objective function in (2), we obtain

$$V(d, w_f) = \begin{cases} \frac{(1-\eta d)^2}{2k}(p + \delta d - w_f)(w_f - c) & \text{if } c \le w_f < \frac{2k}{1-\eta d} + c \\ (1-\eta d)(p + \delta d - w_f) & \text{if } w_f \ge \frac{2k}{1-\eta d} + c. \end{cases}$$

Note that for $w_f \ge \frac{2k}{1-\eta d} + c$ we have $\frac{\partial V(d,w_f)}{\partial w_f} < 0$, so that $w_f^*(d) \le \frac{2k}{1-\eta d} + c$. For $w_f < \frac{2k}{1-\eta d} + c$, as $V(d, w_f)$ is concave in w_f given d and the first-order condition is $\frac{\partial V(d,w_f)}{\partial w_f} = p + \delta d - 2w_f + c = 0$, we can obtain the optimal wholesale price for given d as follows:

$$w_f^*(d) = \begin{cases} \frac{p+\delta d+c}{2}, & \text{if } p + \delta d - c < \frac{4k}{1-\eta d} \\ \frac{2k}{1-\eta d} + c, & \text{if } p + \delta d - c \ge \frac{4k}{1-\eta d}. \end{cases}$$

Given our assumption $4k > p + \delta - c$, this simplifies to $w_f^*(d) = \frac{p+\delta d+c}{2}$, which we substitute into (2) to obtain $R(d) = \frac{(1-\eta d)^2(p+\delta d-c)^2}{8k}$. Hence, $R(0) = \frac{(p-c)^2}{8k}$ and $R(1) = \frac{(1-\eta)^2(p+\delta-c)^2}{8k}$. Comparing $R(1)$ and $R(0)$ is equivalent to comparing $p-c$ with $(1-\eta)(p+\delta-c)$. Let us define $\hat{\eta} = \frac{\delta}{p+\delta-c}$. Then $d^* = 1$ if $\eta < \hat{\eta}$ and 0 if $\eta \ge \hat{\eta}$. We substitute d^* into the expression of $w_f^*(d)$ and $e^*(d, w_f)$ in the following two cases: If $\eta < \hat{\eta}$, $d^* = 1$. We have $w_f^* = \frac{1}{2}(p + \delta + c)$ and, using Lemma 1, $e^* = \frac{(1-\eta)(p+\delta-c)}{4k}$. If $\hat{\eta} \le \eta$, $d^* = 0$. We have $w_f^* = \frac{1}{2}(p + c)$ and, using Lemma 1, $e^* = \frac{p-c}{4k}$.

Proof of Corollary 1: For $\hat{\eta} \le \eta < 1$, as $(d^*, e^*) = (0, \frac{p-c}{4k})$, we have $L^* = 1 - (1-\eta d^*)e^* = 1 - \frac{p-c}{4k}$. For $\eta < \hat{\eta}$, as $(d^*, e^*) = (1, \frac{(1-\eta)(p+\delta-c)}{4k})$, we have $L^* = 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k}$.

Proof of Proposition 2:

- Fix δ. For $\eta \in (0, \hat{\eta})$, we have $L^* = L(1) = 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k}$, so $\frac{dL^*}{d\eta} > 0$. For $\eta \in [\hat{\eta}, 1)$, we have $L^* = L(0) = 1 - \frac{p-c}{4k}$, so $\frac{dL^*}{d\eta} = 0$. At $\eta = \hat{\eta}$, we have $L(1) > L(0)$ because $1 - \frac{(1-\hat{\eta})^2(p+\delta-c)}{4k} > 1 - \frac{p-c}{4k} \Leftrightarrow p - c > (1-\hat{\eta})^2(p+\delta-c) \Leftrightarrow 1 > \frac{p-c}{p+\delta-c}$. Therefore, L^* experiences a discontinuous decrease at $\eta = \hat{\eta}$.

- Fix η. First, we use the threshold $\hat{\eta} = \frac{\delta}{p+\delta-c}$ to define the complementary threshold $\hat{\delta} = \frac{\eta(p-c)}{1-\eta}$. For $\delta \in [0, \hat{\delta}]$, we have $L^* = L(0) = 1 - \frac{p-c}{4k}$, so $\frac{dL^*}{d\delta} = 0$. For $\delta \in (\hat{\delta}, \infty)$, we have $L^* = L(1) = 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k}$, so $\frac{dL^*}{d\delta} < 0$. At $\delta = \hat{\delta}$, we have $1 - \frac{p-c}{4k} < 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k}$. Therefore, L^* experiences a discontinuous increase at $\delta = \hat{\delta}$.

Proof of Proposition 3: We substitute $d \in \{0, 1\}$ into $w_f^*(d)$ and then into $e^*(d, w_f)$ to obtain $L(0) = 1 - \frac{p-c}{4k}$ and $L(1) = 1 - \frac{(1-\eta)^2(p+\delta-c)}{4k}$. Hence, $L(1) < L(0)$ for $\eta < \overline{\eta} = 1 - \sqrt{\frac{p-c}{p+\delta-c}}$, and $L(1) > L(0)$ otherwise. We can also show that $\hat{\eta} > \overline{\eta}$, as $\hat{\eta} - \overline{\eta} = \sqrt{\frac{p-c}{p+\delta-c}} - \frac{p-c}{p+\delta-c} > 0$.

Proof of Lemma 2: The retailer's revenue function $V(d, w_f)$ at $t = 4$ is obtained via optimizing over the retail price r as follows:

$$
\begin{aligned}
V(d, w_f) &= \max_r r \min\{1 + \mu d - r, (1-\eta d)e\} \\
&= \max\left\{\max_{r > 1+\mu d-(1-\eta d)e} r(1 + \mu d - r), \max_{r \leq 1+\mu d-(1-\eta d)e} r(1-\eta d)e\right\} \\
&= \max_{r \geq 1+\mu d-(1-\eta d)e} r(1 + \mu d - r),
\end{aligned}
$$

where the last equality is because the second term in the max operator in the second line increases in r. Thus, we have

$$
r^*(d, w_f, e) = \begin{cases} \frac{1+\mu d}{2} & \text{if } e > \frac{1+\mu d}{2(1-\eta d)} \\ 1 + \mu d - (1-\eta d)e & \text{if } e \leq \frac{1+\mu d}{2(1-\eta d)} \end{cases}.
$$

We consider the following two cases depending on the wholesale price:

(a) If $c < w_f < \frac{2k}{1-\eta d} + c$: In this case, $e^*(d, w_f) = \frac{(1-\eta d)(w_f - c)}{2k}$ base on Lemma 1. We can easily show that for $\frac{k(1+\mu d)}{(1-\eta d)^2} + c < w_f$, we have $e^*(d, w_f) > \frac{1+\mu d}{2(1-\eta d)}$, whereas for $w_f \leq \frac{k(1+\mu d)}{(1-\eta d)^2} + c$ we have $e^*(d, w_f) \leq \frac{1+\mu d}{2(1-\eta d)}$. We substitute the optimal retail price $r^*(d, w_f, e)$ and sales quantity into the retailer's profit function in period $t = 1$ and obtain:

$$
V(d, w_f) = \begin{cases} \frac{(1+\mu d)^2}{4} - \frac{(1-\eta d)^2(w_f - c)w_f}{2k} & \text{if } \min\left\{\frac{k(1+\mu d)}{(1-\eta d)^2} + c, \frac{2k}{1-\eta d} + c\right\} < w_f < \frac{2k}{1-\eta d} + c \\ (1 + \mu d - \frac{(1-\eta d)^2(w_f - c)}{2k} - w_f)\frac{(1-\eta d)^2(w_f - c)}{2k} & \text{if } c < w_f \leq \min\left\{\frac{k(1+\mu d)}{(1-\eta d)^2} + c, \frac{2k}{1-\eta d} + c\right\}. \end{cases}
$$

Note that $\frac{k(1+\mu d)}{(1-\eta d)^2} + c < \frac{2k}{1-\eta d} + c$ if and only if $1 - \eta d > \frac{1+\mu d}{2}$.

(b) If $w_f \geq \frac{2k}{1-\eta d} + c$: In this case, $e^*(d, w_f) = 1$ based on Lemma 1. We can easily show that for $1 - \eta d > \frac{1+\mu d}{2}$, we have $e^*(d, w_f) = 1 > \frac{1+\mu d}{2(1-\eta d)}$, whereas for $1 - \eta d \leq \frac{1+\mu d}{2}$ we have $e^*(d, w_f) = 1 \leq \frac{1+\mu d}{2(1-\eta d)}$. We substitute the optimal retail price $r^*(d, w_f, e)$ and sales quantity into the retailer's period function in period $t = 1$ and obtain

$$
V(d, w_f) = \begin{cases} \frac{(1+\mu d)^2}{4} - w_f(1-\eta d) & \text{if } 1 - \eta d > \frac{1+\mu d}{2} \\ (\eta d + \mu d - w_f)(1-\eta d) & \text{if } 1 - \eta d \leq \frac{1+\mu d}{2}. \end{cases}
$$

Combining the two cases above, we summarize as follows:

(a) For $1-\eta d > \frac{1+\mu d}{2}$, we have:

$$V(d,w_f) = \begin{cases} (1+\mu d - \frac{(1-\eta d)^2(w_f-c)}{2k} - w_f)\frac{(1-\eta d)^2(w_f-c)}{2k} & \text{if } c < w_f \le \frac{k(1+\mu d)}{(1-\eta d)^2}+c \\ \frac{(1+\mu d)^2}{4} - \frac{(1-\eta d)^2(w_f-c)w_f}{2k} & \text{if } \frac{k(1+\mu d)}{(1-\eta d)^2}+c < w_f < \frac{2k}{1-\eta d}+c \\ \frac{(1+\mu d)^2}{4} - w_f(1-\eta d) & \text{if } w_f \ge \frac{2k}{1-\eta d}+c. \end{cases}$$

Note that for $w_f > \frac{k(1+\mu d)}{(1-\eta d)^2}+c$, we can show that $V(d,w_f)$ is decreasing in w_f. Therefore, we limit ourselves to $c < w_f \le \frac{k(1+\mu d)}{(1-\eta d)^2}+c$. $V(d,w_f)$ is concave over that range, and its maximizer is $w_f^*(d) = \frac{k(1+\mu d-c)}{2k+(1-\eta d)^2}+c \in (c, \frac{k(1+\mu d)}{(1-\eta d)^2}+c]$. We have $R(d) = \frac{(1+\mu d-c)^2(1-\eta d)^2}{4(2k+(1-\eta d)^2)}$.

(b) For $1-\eta d \le \frac{1+\mu d}{2}$, we have:

$$V(d,w_f) = \begin{cases} (1+\mu d - \frac{(1-\eta d)^2(w_f-c)}{2k} - w_f)\frac{(1-\eta d)^2(w_f-c)}{2k} & \text{if } c < w_f < \frac{2k}{1-\eta d}+c \\ (\eta d + \mu d - w_f)(1-\eta d) & \text{if } w_f \ge \frac{2k}{1-\eta d}+c. \end{cases}$$

Note that for $w_f \ge \frac{2k}{1-\eta d}+c$, $V(d,w_f)$ is decreasing in w_f; the optimal wholesale price must be within $c < w_f \le \frac{2k}{1-\eta d}+c$, with the same revenue function as in the first case. We verify whether $\frac{k(1+\mu d-c)}{2k+(1-\eta d)^2}+c < \frac{2k}{1-\eta d}+c$, which holds given our assumption $4k > (1-\eta d)(1+\mu d - c - 2(1-\eta d))$. Therefore, we have $w_f^*(d) = \frac{k(1+\mu d-c)}{2k+(1-\eta d)^2}+c$ and $R(d) = \frac{(1+\mu d-c)^2(1-\eta d)^2}{4(2k+(1-\eta d)^2)}$.

We compare $R(0) = \frac{(1-c)^2}{4(1+2k)}$ and $R(1) = \frac{(1+\mu-c)^2(1-\eta)^2}{4(2k+(1-\eta)^2)}$ and find that $R(1) \ge R(0)$ if and only if $\eta \le 1 - \sqrt{\frac{2k(1-c)^2}{2k(1+\mu-c)^2+\mu(2+\mu-2c)}}$, and $R(1) > R(0)$ otherwise. We denote $\hat{\eta}' = 1 - \sqrt{\frac{2k(1-c)^2}{2k(1+\mu-c)^2+\mu(2+\mu-2c)}}$. We have $d^* = 1$ if $\eta \le \hat{\eta}'$, and $d^* = 0$ otherwise. Substituting d^* into the expression of $w_f^*(d)$, $e^*(d,w_f)$, and $r^*(d,w_f,e)$, we obtain the following equilibrium outcomes:

$$(d^*, w_f^*, e^*, r^*) = \begin{cases} \left(0, \frac{k(1-c)}{1+2k}+c, \frac{1-c}{2(1+2k)}, \frac{1+c+4k}{2(1+2k)}\right) & \text{if } \eta > \hat{\eta}' \\ \left(1, \frac{k(1+\mu-c)}{2k+(1-\eta)^2}+c, \frac{(1+\mu-c)(1-\eta)}{2(2k+(1-\eta)^2)}, \frac{(1+\mu+c)(1-\eta)^2+4k(1+\mu)}{2(2k+(1-\eta)^2)}\right) & \text{if } \eta \le \hat{\eta}'. \end{cases}$$

Proof of Proposition 4: For notational simplicity, we define $\bar{w}_f(d) := \sqrt{\frac{4kg_H}{y_H-1}}\frac{1}{1-\eta d}+c$. We consider two cases: $y_H > 1+\frac{g_H}{k}$ and $y_H \le 1+\frac{g_H}{k}$.

If $y_H > 1+\frac{g_H}{k}$, substituting the optimal effort level and yield decision in Lemma A.1 into (5), we obtain the retailer's optimization as follows:

$$\begin{aligned} R(d) &= \max \begin{Bmatrix} \max_{c \le w_f < \bar{w}_f(d)} \frac{(p+\delta d-w_f)(w_f-c)(1-\eta d)^2}{2k}, \\ \max_{\bar{w}_f(d) \le w_f < \frac{2k}{1-\eta d}+c} \frac{y_H(p+\delta d-w_f)(w_f-c)(1-\eta d)^2}{2k}, \\ \max_{w_f \ge \frac{2k}{1-\eta d}+c} y_H(p+\delta d - w_f)(1-\eta d) \end{Bmatrix} \\ &= \max\{R_1(d), R_2(d), R_3(d)\} \end{aligned}$$

The unconstrained maximizer for the first and second optimizations is $w_f = \frac{p+\delta d+c}{2}$. From the assumption $4k > p+\delta-c$, we know that $\frac{p+\delta d+c}{2} < \frac{2k}{1-\eta d}+c$ for $d \in \{0,1\}$, so the third optimization can be eliminated. For convenience, we define $\eta_1(d) = 1 - \sqrt{\frac{16kg_H}{y_H-1}\frac{y_H-\sqrt{y_H(y_H-1)}}{p+\delta d-c}}$ and $\eta_2(d) = 1 - \sqrt{\frac{16kg_H}{(y_H-1)(p+\delta d-c)^2}}$. As $y_H - \sqrt{y_H(y_H-1)} < 1$, we know $\eta_1(d) > \eta_2(d)$. We consider the following two cases:

(a) $\frac{p+\delta d+c}{2} < \bar{w}_f(d) \Longleftrightarrow \eta d > \eta_2(d)$. We have $R_1(d) = \frac{(1-\eta d)^2(p+\delta d-c)^2}{8k}$ and $R_2(d) = \sqrt{\frac{g_H}{k(y_H-1)}}y_H(1-\eta d)(p+\delta d-c) - \frac{2g_H y_H}{y_H-1}$. We find that $R_2(d) > R_1(d) \Leftrightarrow \eta d < \eta_1(d)$. So, $w_f^*(d)$ is as follows: $w_f^*(d) = \frac{p+\delta d+c}{2}$ if $\eta d > \eta_1(d)$; $w_f^*(d) = \bar{w}_f(d)$ if $\eta_2(d) < \eta d \leq \eta_1(d)$.

(b) $\bar{w}_f(d) \leq \frac{p+\delta d+c}{2} < \frac{2k}{1-\eta d} + c \Longleftrightarrow \eta d \leq \eta_2(d)$. We have $R_2(d) = \frac{(1-\eta d)^2(p+\delta d-c)^2}{8k} = y_H R_1(d)$, so $R_2(d) > R_1(d)$. The optimal wholesale price $w_f^*(d) = \frac{p+\delta d+c}{2}$.

Combining the cases (a) and (b), we obtain

$$w_f^*(d) = \begin{cases} \frac{p+\delta d+c}{2} & \text{if } \eta d \geq \eta_1(d) \\ \bar{w}_f(d) & \text{if } \eta_2(d) < \eta d < \eta_1(d) \\ \frac{p+\delta d+c}{2} & \text{if } \eta d \leq \eta_2(d) \end{cases} \tag{A.1}$$

Substituting $w_f^*(d)$ into the retailer's objective function, we obtain $R(d)$ as follows:

$$R(d) = \begin{cases} \frac{(1-\eta d)^2(p+\delta d-c)^2}{8k} & \text{if } \eta d \geq \eta_1(d) \\ \sqrt{\frac{g_H y_H^2}{k(y_H-1)}}(1-\eta d)(p+\delta d-c) - \frac{2g_H y_H}{y_H-1} & \text{if } \eta_2(d) < \eta d < \eta_1(d) \\ \frac{y_H(1-\eta d)^2(p+\delta d-c)^2}{8k} & \text{if } \eta d \leq \eta_2(d) \end{cases}$$

For $d \in \{0,1\}$, we define $\underline{y}_H^{(d)}$ as the positive solution to $\eta_1(d) = 0$, and $\overline{y}_H^{(d)} = 1 + \frac{16kg_H}{(p+\delta d-c)^2}$ as the solution to $\eta_2(d) = 0$. We can easily show $\overline{y}_H^{(d)} > \underline{y}_H^{(d)}$, $\overline{y}_H^{(1)} < \overline{y}_H^{(0)}$, and $\underline{y}_H^{(1)} < \underline{y}_H^{(0)}$. If $\delta > \frac{(p-c)(1-(y_H-\sqrt{y_H(y_H-1)}))}{y_H-\sqrt{y_H(y_H-1)}}$, $\overline{y}_H^{(1)} < \underline{y}_H^{(0)}$; otherwise, $\overline{y}_H^{(1)} \geq \underline{y}_H^{(0)}$.

To obtain the optimal d^*, we compare $R(1)$ and $R(0)$ in the following three cases: $\eta_1(0) \leq 0$, $\eta_2(0) < 0 < \eta_1(0)$, and $\eta_2(0) \geq 0$.

1. $\eta_1(0) \leq 0 \Leftrightarrow y_H \leq \underline{y}_H^{(0)}$, which also corresponds to $p - c \leq \sqrt{\frac{16kg_H}{y_H-1}}(y_H - \sqrt{y_H(y_H-1)})$. We have $R(0) = \frac{(p-c)^2}{8k}$. We compare $R(0)$ with $R(1)$ in the following three sub-cases:

   (i) If $\eta \geq \eta_1(1)$, then $R(1) = \frac{(1-\eta)^2(p+\delta-c)^2}{8k}$. Because $\eta_1(1)-\hat{\eta} = \frac{1}{p+\delta-c}(p-c-\sqrt{\frac{16kg_H}{y_H-1}}(y_H - \sqrt{y_H(y_H-1)})) < 0)$, we obtain from Proposition 1 that $d^* = 1$ if $\eta_1(1) \leq \eta < \hat{\eta}$ and $d^* = 0$ if $\eta \geq \hat{\eta}$.

   (ii) If $\eta_2(1) < \eta < \eta_1(1)$, then $R(1) = \sqrt{\frac{g_H y_H^2}{k(y_H-1)}}(1-\eta)(p+\delta-c) - \frac{2g_H y_H}{y_H-1}$. From $p - c \leq \sqrt{\frac{16kg_H}{y_H-1}}(y_H - \sqrt{y_H(y_H-1)})$, we have $R(0) \leq \frac{2y_H g_H}{y_H-1}(2y_H - 2\sqrt{y_H(y_H-1)} - 1)$. From $\eta < \eta_1(1)$, we obtain $(1-\eta)(p+\delta-c) > \sqrt{\frac{16kg_H}{y_H-1}}(y_H - \sqrt{y_H(y_H-1)})$, so $R(1) \geq \frac{2y_H g_H}{y_H-1}(2y_H - 2\sqrt{y_H(y_H-1)} - 1) \geq R(0)$. Hence, $d^* = 1$.

   (iii) If $0 \leq \eta \leq \eta_2(1)$, then $R(1) = \frac{y_H(1-\eta)^2(p+\delta-c)^2}{8k}$. From $(1-\eta)(p+\delta-c) > \sqrt{\frac{16kg_H}{y_H-1}}(y_H - \sqrt{y_H(y_H-1)})$, we show $R(1) \geq \frac{2y_H g_H}{y_H-1}(2y_H - 2\sqrt{y_H(y_H-1)} - 1) \geq R(0)$. Hence, $d^* = 1$.

2. $\eta_2(0) < 0 < \eta_1(0) \Leftrightarrow \underline{y}_H^{(0)} < y_H < \overline{y}_H^{(0)}$, which corresponds to $\sqrt{\frac{16kg_H}{y_H-1}}(y_H - \sqrt{y_H(y_H-1)}) < p - c < \sqrt{\frac{16kg_H}{y_H-1}}$. We compare $R(0) = \sqrt{\frac{g_H y_H^2}{k(y_H-1)}}(p-c) - \frac{2g_H y_H}{y_H-1}$ with $R(1)$ in the following:

(i) If $\eta \geq \eta_1(1)$, then $R(1) = \frac{(1-\eta)^2(p+\delta-c)^2}{8k}$. From $p - c > \sqrt{\frac{16kg_H}{(y_H-1)}}(y_H - \sqrt{y_H(y_H-1)})$, we have $R(0) > \frac{2g_H y_H}{y_H-1}$. From $\eta \geq \eta_1(1)$, we have $(1-\eta)(p+\delta-c) \leq \sqrt{\frac{16kg_H}{y_H-1}}(y_H - \sqrt{y_H(y_H-1)})$ and thus $R(1) \leq \frac{2g_H y_H}{y_H-1}$. Hence, $d^* = 0$.

(ii) If $\eta_2(1) < \eta < \eta_1(1)$, then $R(1) = \sqrt{\frac{g_H y_H^2}{k(y_H-1)}}(1-\eta)(p+\delta-c) - \frac{2g_H y_H}{y_H-1}$. Note that $\sqrt{\frac{16kg_H}{y_H-1}}(y_H - \sqrt{y_H(y_H-1)}) < p - c < \sqrt{\frac{16kg_H}{y_H-1}}$ implies $\eta_2(1) < \hat{\eta} < \eta_1(1)$. We have $d^* = 1$ if $\eta_1(1) < \eta < \hat{\eta}$ and $d^* = 0$ if $\hat{\eta} \leq \eta < \eta_1(1)$.

(iii) If $0 \leq \eta \leq \eta_2(1)$, then $R(1) = \frac{y_H(1-\eta)^2(p+\delta-c)^2}{8k}$. From $p - c < \sqrt{\frac{16kg_H}{(y_H-1)}}$, we have $R(0) < \frac{2y_H g_H}{y_H-1}$. From $\eta < \eta_2(1)$, we have $(1-\eta)(p+\delta-c) > \sqrt{\frac{16kg_H}{y_H-1}}$ and thus $R(1) \geq \frac{2y_H g_H}{y_H-1} > R(0)$. Hence, $d^* = 1$.

3. $\eta_2(0) \geq 0 \Leftrightarrow y_H \geq \overline{y}_H^{(0)}$, which corresponds to $p - c \geq \sqrt{\frac{16kg_H}{y_H-1}}$. We compare $R(0) = \frac{y_H(p-c)^2}{8k}$ with $R(1)$ in the following three sub-cases:

(i) If $\eta \geq \eta_1(1)$, then $R(1) = \frac{(1-\eta)^2(p+\delta-c)^2}{8k}$. From $p - c > \sqrt{\frac{16kg_H}{(y_H-1)}}$, we have $R(0) \geq \frac{2g_H y_H}{y_H-1}$. From $\eta \geq \eta_1(1)$, we have $(1-\eta)(p+\delta-c) \leq \sqrt{\frac{16kg_H}{y_H-1}}(y_H - \sqrt{y_H(y_H-1)})$, and thus $R(1) < \frac{2g_H y_H}{y_H-1}$. Hence, $d^* = 0$.

(ii) If $\eta_2(1) < \eta < \eta_1(1)$, then $R(1) = \sqrt{\frac{g_H y_H^2}{k(y_H-1)}}(1-\eta)(p+\delta-c) - \frac{2g_H y_H}{y_H-1}$. From $\eta > \eta_2(1)$, we have $(1-\eta)(p+\delta-c) < \sqrt{\frac{16kg_H}{y_H-1}}$ and thus $R(1) < \frac{2g_H y_H}{y_H-1} < R(0)$. Hence, $d^* = 0$.

(iii) If $0 \leq \eta \leq \eta_2(1)$, then $R(1) = \frac{y_H(1-\eta)^2(p+\delta-c)^2}{8k}$. Note that $p - c > \sqrt{\frac{16kg_H}{y_H-1}}$ implies $\eta_2(1) > \hat{\eta}$. We have $d^* = 1$ if $\eta < \hat{\eta}$ and $d^* = 0$ if $\hat{\eta} \leq \eta \leq \eta_2(1)$.

Combining all the cases, we find that $d^* = 1$ if $\eta < \hat{\eta}$; otherwise, $d^* = 0$. Substituting the optimal d^* into (A.1) and then into the optimal farmer efforts in Lemma A.1, we obtain the equilibrium (d^*, w_f^*, e^*, a^*) as follows:

- If $1 + \frac{g_H}{k} < y_H \leq \underline{y}_H^{(0)}$, the equilibrium (d^*, w_f^*, e^*, a^*) is as follows:

$$(d^*, w_f^*, e^*, a^*) = \begin{cases} (0, \frac{p+c}{2}, \frac{p-c}{4k}, 0) & \text{if } \hat{\eta} < \eta < 1 \\ (1, \frac{p+\delta+c}{2}, \frac{(1-\eta)(p+\delta-c)}{4k}, 0) & \text{if } \eta_1(1) < \eta \leq \hat{\eta} \\ (1, \sqrt{\frac{4kg_H}{(y_H-1)(1-\eta)^2}} + c, \sqrt{\frac{g_H}{k(y_H-1)}}, 1) & \text{if } \eta_2(1) < \eta \leq \eta_1(1) \\ (1, \frac{p+\delta+c}{2}, \frac{(1-\eta)(p+\delta-c)}{4k}, 1) & \text{if } 0 \leq \eta \leq \eta_2(1) \end{cases}$$

- If $\underline{y}_H^{(0)} < y_H \leq \overline{y}_H^{(0)}$, the equilibrium (d^*, w_f^*, e^*, a^*) is as follows:

$$(d^*, w_f^*, e^*, a^*) = \begin{cases} (0, \sqrt{\frac{4kg_H}{y_H-1}} + c, \sqrt{\frac{g_H}{k(y_H-1)}}, 1) & \text{if } \hat{\eta} < \eta < 1 \\ (1, \sqrt{\frac{4kg_H}{(y_H-1)(1-\eta)^2}} + c, \sqrt{\frac{g_H}{k(y_H-1)}}, 1) & \text{if } \eta_2(1) < \eta \leq \hat{\eta} \\ (1, \frac{p+\delta+c}{2}, \frac{(1-\eta)(p+\delta-c)}{4k}, 1) & \text{if } 0 \leq \eta \leq \eta_2(1) \end{cases}$$

- If $y_H > \overline{y}_H^{(0)}$, the equilibrium (d^*, w_f^*, e^*, a^*) is as follows:

$$(d^*, w_f^*, e^*, a^*) = \begin{cases} (0, \frac{p+c}{2}, \frac{p-c}{4k}, 1) & \text{if } \hat{\eta} < \eta < 1 \\ (1, \frac{p+\delta+c}{2}, \frac{(1-\eta)(p+\delta-c)}{4k}, 1) & \text{if } 0 \le \eta \le \hat{\eta} \end{cases}$$

For ease of notation, we denote $\underline{y}_H$ as the positive solution to $\eta_1(d^*) = \eta d^*$ and $\overline{y}_H$ as the positive solution to $\eta_2(d^*) = \eta d^*$. We also observe that d^* is independent of y_H. Therefore, we can regroup all the equilibria described above as follows in three cases as a function of y_H:

$$(d^*, w_f^*, e^*, a^*) = \begin{cases} (d^*, \frac{p+\delta d^*+c}{2}, \frac{(1-\eta d^*)(p+\delta d^*-c)}{4k}, 0) & \text{if } y_H \le \underline{y}_H \\ (d^*, \sqrt{\frac{4kg_H}{(y_H-1)(1-\eta d^*)^2}} + c, \frac{g_H}{k(y_H-1)}, 1) & \text{if } \underline{y}_H < y_H < \overline{y}_H \\ (d^*, \frac{p+\delta d^*+c}{2}, \frac{(1-\eta d^*)(p+\delta d^*-c)}{4k}, 1) & \text{if } y_H \ge \overline{y}_H \end{cases}$$

Furthermore, we can show that the wholesale price $\sqrt{\frac{4kg_H}{(y_H-1)(1-\eta d^*)^2}} + c > \frac{p+\delta d^*+c}{2}$ when $\underline{y}_H < y_H < \overline{y}_H$. For the cosmetic quality effort e^*, we have $\sqrt{\frac{g_H}{k(y_H-1)}} > \frac{(1-\eta d^*)(p+\delta d^*-c)}{4k}$ when $\underline{y}_H < y_H < \overline{y}_H$.

<u>If $1 \le y_H \le 1 + \frac{g_H}{k}$</u>, we have $\eta_1(d) \le 0$, and $a^* = 0$ is always optimal. The equilibrium remains identical to the base model.

Combining the cases when $1 \le y_H \le 1 + \frac{g_H}{k}$ and $y_H > 1 + \frac{g_H}{k}$, we obtain Proposition 4.

Proof of Proposition 5: From Lemma A.2, we know that for $y_H \le \underline{y}_H$ or $y_H \ge \overline{y}_H$, we have $l^* = 1 - \frac{(1-\eta d^*)^2(p+\delta d^*-c)}{4k}$, which is the same as L^* in the base case. For $\underline{y}_H < y_H < \overline{y}_H$, we have $l^* = 1 - (1-\eta d^*)\sqrt{\frac{g_H}{k(y_H-1)}} < 1 - \frac{(1-\eta d^*)^2(p+\delta d^*-c)}{4k}$, with $\frac{\partial l^*}{\partial y_H} > 0$.

Proof of Proposition 6: We use the same proof as in Proposition 1 except replacing c with $\bar{c} = c + (w_p - c)\xi$. The equilibrium outcomes are $(d^*, w_f^*, e^*) = (0, \frac{p+\bar{c}}{2}, \frac{p-\bar{c}}{4k})$ when $\eta > \frac{\delta}{p+\delta-\bar{c}}$ and $(d^*, w_f^*, e^*) = (1, \frac{p+\delta+\bar{c}}{2}, \frac{(1-\eta)(p+\delta-\bar{c})}{4k})$ otherwise. We can show $\frac{\delta}{p+\delta-\bar{c}} > \hat{\eta}$ and $\frac{p+\delta d+\bar{c}}{2} > \frac{p+\delta d+c}{2}$ since $\bar{c} > c$.

Proof of Proposition 7: Note that $\eta = \frac{\delta}{p+\delta-(c+\xi(w_p-c))}$ can be equivalently written as $\xi = \frac{\eta(p+\delta-c)-\delta}{\eta(w_p-c)}$. For $\xi \in [0,1)$, we can write food loss in equilibrium as follows: $L^* = L(0) = (1-\xi)(1-\frac{p-\bar{c}}{4k})$ if $\xi \in \left[0, \frac{\eta(p+\delta-c)-\delta}{\eta(w_p-c)}\right]$, with $\frac{dL^*}{d\xi} < 0$; and $L^* = L(1) = (1-\xi)(1-\frac{(1-\eta)^2(p+\delta-\bar{c})}{4k})$ if $\xi \in \left(\frac{\eta(p+\delta-c)-\delta}{\eta(w_p-c)}, 1\right)$, with $\frac{dL^*}{d\xi} < 0$. At $\xi = \frac{\eta(p+\delta-c)-\delta}{\eta(w_p-c)}$, we have $L(0) = (1-\xi)(1-\frac{p-\bar{c}}{4k}) < (1-\xi)(1-\frac{(1-\eta)^2(p+\delta-\bar{c})}{4k}) = L(1)$. Therefore, L^* experiences a discontinuous increase at $\xi = \frac{\eta(p+\delta-c)-\delta}{\eta(w_p-c)}$ and decreases for all other ξ.

Proof of Proposition 8: We follow the same proof of Proposition 3 except replacing c with $\bar{c}$.

Proof of Proposition 9: We denote $\bar{w}_f^B(d) = \frac{2k}{1-\eta d} + c$ and $\bar{w}_f^L(d) = \frac{4k}{1-\eta d} + c - \epsilon$, the wholesale price at which the farmer exerts maximum effort when harvesting under both costs (with superscript B) and under only low cost (with superscript L), respectively. Based on Lemma A.4, for a given $d \in \{0,1\}$, we need to consider two cases: $0 \le \epsilon \le \frac{2k}{1-\eta d}$ and $\epsilon > \frac{2k}{1-\eta d}$.

<u>If $0 \le \epsilon \le \frac{2k}{1-\eta d}$</u>, we substitute $e^*(d, w_f)$ into the retailer's objective function and obtain

$$R(d) = \max_{w_f \ge c-\epsilon} (p + \delta d - w_f)\frac{\mathbf{I}\{w_f \ge c+\epsilon\} + 1}{2}(1-\eta d)e(d, w_f) = \max\left\{R^L(d), R^B(d)\right\}$$

where

$$R^L(d) = \frac{(1-\eta d)^2}{8k} \max_{c-\epsilon \le w_f < c+\epsilon} (p + \delta d - w_f)(w_f - c + \epsilon), \tag{A.2}$$

$$R^B(d) = \frac{(1-\eta d)^2}{2k} \max_{c+\epsilon \le w_f < \bar{w}_f^B(d)} (p + \delta d - w_f)(w_f - c). \tag{A.3}$$

Let us define two optimizers to the following two unconstrained optimization:

$$w_f^L(d) = \frac{p + \delta d + c - \epsilon}{2} = \underset{w_f}{\mathrm{argmax}}(p + \delta d - w_f)(w_f - c + \epsilon),$$

$$w_f^B(d) = \frac{p + \delta d + c}{2} = \underset{w_f}{\mathrm{argmax}}(p + \delta d - w_f)(w_f - c).$$

We note that $w_f^B \in [c+\epsilon, \bar{w}_f^B(d))$ holds if and only if $\epsilon \le \min\left\{\frac{2k}{1-\eta d}, \frac{p+\delta d-c}{2}\right\} = \frac{p+\delta d-c}{2}$, where the equality follows from $\frac{p+\delta d-c}{2} < \frac{2k}{1-\eta d}$, which holds by assumption. We also note that $w_f^L(d) \in [c-\epsilon, c+\epsilon)$ holds if and only if $\epsilon > \frac{p+\delta d-c}{3}$ and $w_f^L(d) > c - \epsilon$. We compare $R^B(d)$ and $R^L(d)$ in the following cases:

(a) If $\epsilon > \frac{p+\delta d-c}{2}$, then $w_f^L(d) \in [c-\epsilon, c+\epsilon)$ is the optimal solution to (A.2) and $R^L(d) = \frac{(1-\eta d)^2(p+\delta d-c+\epsilon)^2}{32k}$. However, $w_f^B(d) < c + \epsilon$, so the optimal solution to (A.3) is $w_f = c + \epsilon$. We have $R^B(d) = \frac{(1-\eta d)^2(p+\delta d-c-\epsilon)\epsilon}{2k}$. From the comparison of $R^L(d)$ and $R^B(d)$, the optimal solution is $w_f = c+\epsilon$ if $\epsilon < \min\left\{\frac{2k}{1-\eta d}, \frac{(7+4\sqrt{2})(p+\delta d-c)}{17}\right\}$ and $w_f^L(d)$ if $\frac{(7+4\sqrt{2})(p+\delta d-c)}{17} \le \epsilon < \frac{2k}{1-\eta d}$. Note that $\frac{(7+4\sqrt{2})(p+\delta d-c)}{17} < 2k \le \frac{2k}{1-\eta d}$ holds by assumption.

(b) If $\frac{p+\delta d-c}{3} < \epsilon \le \frac{p+\delta d-c}{2}$, then $w_f^L(d) \in [c-\epsilon, c+\epsilon)$ and $R^L(d) = \frac{(1-\eta d)^2(p+\delta d-c+\epsilon)^2}{32k}$. Also, $w_f^B(d) \in [c+\epsilon, \bar{w}_f^B(d))$ and $R^B(d) = \frac{(1-\eta d)^2(p+\delta d-c)^2}{8k}$. From $\epsilon \le p + \delta d - c$, we have $R^B(d) > R^L(d)$, and $w_f(d) = w_f^B(d)$.

(c) If $\epsilon \le \frac{p+\delta d-c}{3}$, then $w_f^L(d) > c + \epsilon$ and the optimal solution to (A.2) is $w_f = c+\epsilon$. However, this is a feasible solution to (A.3) so that the solution to (A.3) is optimal. We have $w_f^B(d) \in [c+\epsilon, \bar{w}_f^B(d))$, so $w_f(d) = w_f^B(d)$.

<u>If $\epsilon > \frac{2k}{1-\eta d}$,</u> we have

$$R(d) = \max\left\{\max_{c-\epsilon \le w_f \le \bar{w}_f^L(d)} (p + \delta d - w_f)\frac{(1-\eta d)^2(w_f - c + \epsilon)}{8k}, \max_{w_f \ge c+\epsilon}(p + \delta d - w_f)(1-\eta d)\right\}.$$

From Lemma A.4, when $\epsilon > \frac{2k}{1-\eta d}$, the farmer's effort equals 1 when harvesting under both costs, i.e., when $w_f = c + \epsilon$. Note that $w_f^L(d)$ is the optimal solution to the unconstrained optimization of the first optimization in this expression.

Given $4k > (1-\eta d)\frac{p+\delta d-c+\epsilon}{2}$, it follows that $w_f^L(d) \in [c-\epsilon, \bar{w}_f^L(d)]$. We know $R^L(d) = \frac{(1-\eta d)^2(p+\delta d-c+\epsilon)^2}{32k}$ and $R^B(d) = (1-\eta d)(p + \delta d - c - \epsilon)$. We find that $R^L(d) > R^B(d) \Leftrightarrow \eta d < 1 - \frac{32(p+\delta d-c-\epsilon)}{(p+\delta d-c+\epsilon)^2}$. We can show that $1 - \frac{32(p+\delta d-c-\epsilon)}{(p+\delta d-c+\epsilon)^2} > 1 - \frac{2k}{\epsilon}$ for $\epsilon > \frac{(7+4\sqrt{2})(p+\delta d-c)}{17}$. Then, given the assumption $4k > \frac{2(7+4\sqrt{2})(p+\delta d-c)}{17}$, we have $\epsilon > 2k > \frac{(7+4\sqrt{2})(p+\delta d-c)}{17}$, so that $R^L(d) > R^B(d)$ always holds when $\epsilon > \frac{2k}{1-\eta d}$.

Combining the above cases, given $d \in \{0,1\}$, the optimal $w_f^*(d)$ is given as follows:

$$w_f^*(d) = \begin{cases} w_f^B(d) = \frac{p+\delta d+c}{2}, & \text{if } 0 \le \epsilon \le \frac{p+\delta d-c}{2} \\ c+\epsilon & \text{if } \frac{p+\delta d-c}{2} < \epsilon < \frac{(7+4\sqrt{2})(p+\delta d-c)}{17} \\ w_f^L(d) = \frac{p+\delta d+c-\epsilon}{2}, & \text{if } \epsilon \ge \frac{(7+4\sqrt{2})(p+\delta d-c)}{17} \end{cases}$$

Therefore, given our assumption $4k > \max\left\{\frac{p+\delta-c+\epsilon}{2}, \frac{2(7+4\sqrt{2})(p+\delta-c)}{17}\right\}$, six strategies emerge: $(0, w_f^B(0))$, $(1, w_f^B(1))$, $(0, c+\epsilon)$, $(1, c+\epsilon)$, $(0, w_f^L(0))$, and $(1, w_f^L(1))$. Substituting $w_f^*(d)$ into the retailer's profit, we obtain $R(d)$ for a given $d \in \{0,1\}$ based on the value of ϵ as follows:

$$R(d) = \begin{cases} \frac{(1-\eta d)^2(p+\delta d-c)^2}{8k}, & \text{if } 0 \le \epsilon \le \frac{p+\delta d-c}{2} \\ (1-\eta d)(p+\delta d-c-\epsilon) & \text{if } \frac{p+\delta d-c}{2} < \epsilon < \frac{(7+4\sqrt{2})(p+\delta d-c)}{17} \\ \frac{(1-\eta d)^2(p+\delta d-c+\epsilon)^2}{32k}, & \text{if } \epsilon \ge \frac{(7+4\sqrt{2})(p+\delta d-c)}{17} \end{cases}$$

For ease of notation, we define $\underline{\epsilon}^{(d)} = \frac{p+\delta d-c}{2}$ and $\overline{\epsilon}^{(d)} = \frac{(7+4\sqrt{2})(p+\delta d-c)}{17}$, where $\underline{\epsilon}^{(0)} < \overline{\epsilon}^{(0)}$, $\underline{\epsilon}^{(1)} < \overline{\epsilon}^{(1)}$, and $\overline{\epsilon}^{(0)} < \underline{\epsilon}^{(1)}$ if $\delta > \frac{(8\sqrt{2}-3)(p-c)}{17}$; otherwise $\overline{\epsilon}^{(0)} \ge \underline{\epsilon}^{(1)}$. To determine the optimal d, we perform pairwise comparisons of the retailer's optimal profits under both standards and find that $d^* = 0$ if $\eta > \tilde{\eta}(\epsilon)$ and $d^* = 1$ if $\eta \le \tilde{\eta}(\epsilon)$, where $\tilde{\eta}(\epsilon)$ is as follows:

$$\tilde{\eta}(\epsilon) = \begin{cases} \frac{\delta}{p+\delta-c} & \text{if } 0 \le \epsilon \le \underline{\epsilon}^{(0)} \\ 1 - \frac{(p-c+\epsilon)}{2(p+\delta-c)} & \text{if } \underline{\epsilon}^{(0)} < \epsilon \le \min\{\overline{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\} \\ \frac{\delta}{p+\delta-c-\epsilon} & \text{if } \min\{\overline{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\} < \epsilon \le \max\{\overline{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\}, 0 \le \delta \le \frac{(8\sqrt{2}-3)(p-c)}{17} \\ 1 - \frac{2\sqrt{(p-c-\epsilon)\epsilon}}{p+\delta-c} & \text{if } \min\{\overline{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\} < \epsilon \le \max\{\overline{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\}, \delta > \frac{(8\sqrt{2}-3)(p-c)}{17} \\ 1 - \sqrt{\frac{(p-c+\epsilon)^2}{16\epsilon(p+\delta-c-\epsilon)}} & \text{if } \max\{\overline{\epsilon}^{(0)}, \underline{\epsilon}^{(1)}\} < \epsilon \le \overline{\epsilon}^{(1)} \\ \frac{\delta}{p+\delta-c+\epsilon} & \text{if } \epsilon > \overline{\epsilon}^{(1)} \end{cases}$$

Substituting (d^*, w_f^*) into Lemma A.4, we obtain the equilibrium in Proposition 9.