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Research article

Environmental taxation of plastic bags and substitutes: Balancing marine pollution and climate change

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A B S T R A C T

Several countries have imposed either a ban or a tax on single-use plastic packaging, motivated by their contribution to marine plastic pollution. This may lead consumers to opt for similar unregulated substitutes, potentially undermining or even counteracting the intended effect of the policy instrument. The purpose of this study is to theoretically and empirically compare the environmental and welfare effects of the first-best Pigouvian taxes on both plastic bags and a substitute (paper bags), with two alternative second-best policy instruments: a tax on plastic products alone, and a common uniform tax on all packaging materials. The empirical analysis accounts for two different types of environmental externalities from the use of both bag types: marine pollution and greenhouse gas emissions. It also compares results for two countries, Denmark and the USA, which differ in the demand for plastic and paper bags. The theoretical analysis shows that a unilateral tax on plastic bags should equal the marginal environmental damage of plastic bags minus a fraction of the marginal environmental cost of paper bags, hence being lower than the Pigouvian tax. The optimal common tax should equal a weighted average of the marginal environmental damage of the two bag types and would be lower than the Pigouvian tax on plastics if the marginal external cost of plastic bags exceeds that for paper bags. The empirical analysis shows that for default parameters, the variation in tax level across the studied scenarios is small. It also shows that if Pigouvian taxes cannot be implemented, a common uniform tax on both bag types would result in a higher welfare gain than a tax on plastic bags alone. Sensitivity analysis reveals that the level of the second-best taxes and their associated environmental and welfare impacts are sensitive to assumptions regarding the littering rate and decay rate of plastic bags in the marine environment.

1. Introduction

Marine plastic pollution, which constitutes 60%–95% of the overall marine litter (Walker et al., 1997, 2006; Derraik, 2002), has become one of the global environmental issues demanding urgent attention. Its impact is widespread, affecting virtually every marine and freshwater ecosystem (Beaumont et al., 2019). According to estimates, approximately 8.75 million metric tons of plastic waste entered the oceans in 2010 alone (Jambeck et al., 2015). Packaging material serves as a significant contributor to the proliferation of plastic pollution, responsible for nearly half of the global plastic waste generation.

As plastic pollution has become a significant global concern, many countries have implemented measures aimed at mitigating plastic production and consumption and enhancing plastic recycling practices, particularly in the context of packaging materials. One example is the European Union (EU), which introduced directives to address plastic products. The first directive, Directive (EU) 2015/720, applies to lightweight plastic bags, while the second, Directive (EU) 2019/904, targets single-use plastic products such as fast-food containers and establishes reduction targets for their consumption.

Policymakers have tried to mitigate plastic pollution through different policy instruments. Several countries have taken measures to reduce the consumption of single-use plastics, which contribute to the lion's share of global marine plastic pollution (Schnurr et al., 2018). Notably, the implementation of taxes on single-use plastic bags has gained traction in various countries and has been regarded as a prominent policy measure in Europe, often referred to as the "most popular tax" (Convery et al., 2007). However, a singular tax or ban targeting single-use plastic bags alone may inadvertently prompt consumers to substitute them with other unregulated alternatives like paper or cotton bags. Such an approach, characterized by incomplete environmental regulations, can result in unintended consequences such as leakage,

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wherein the desired effects of the policy instrument are weakened or even counteracted by an increase in environmental damage arising from the increased production or consumption of unregulated substitute products (Fowlie, 2009).

The potential substitution of regulated plastics with unregulated alternatives would be of lesser concern if the latter did not pose any environmental harm, or if their environmental impact was significantly lower than that of the regulated product. However, numerous Life Cycle Analysis (LCA)[1] studies indicate that plant-based substitutes for plastic products may exhibit considerably higher carbon footprints, thereby contributing to a greater extent to climate change (Khoo and Tan, 2010; Muthu et al., 2011, 2012; Kimmel, 2014; Bisinella et al., 2018; Civancik-Uslu et al., 2019; Ahamed et al., 2021).[2] Conversely, plastics, being non-biodegradable and slow to decompose, persist in the aquatic environment for extended periods of time. Consequently, a trade-off arises between marine pollution and greenhouse gas emissions, which influences the selection of policy instruments about packaging materials.

Thus, when evaluating the welfare implications of policy instruments such as bans and taxes, due consideration must be given to the substitution effects as well as the trade-offs between different environmental impacts. Furthermore, the design of these policy instruments should also account for uncertainties surrounding the magnitude of the various environmental impacts. Such uncertainties arise mainly from limited scientific knowledge concerning the scale and severity of damage incurred by marine plastic pollution and climate change.

The primary objective of this study is twofold: (1) to provide a theoretical examination of the optimal design of regulations for plastic bags and their substitutes, considering two distinct types of environmental externalities from the use of both bag types: marine pollution and greenhouse gases emissions, and (2) to empirically assess the environmental and welfare effects of these policy instruments in two countries that exhibit varying demand patterns for plastic and paper bags. The theoretical analysis aims to identify the first-best regulatory solution that achieves efficiency, which can be attained by implementing a Pigouvian tax[3] equivalent to the marginal damage associated with each product (Hanley et al., 2007). However, while the first-best solution serves as a valuable theoretical benchmark, its practical applicability may be limited. Imposing a fully differentiated first-best tax structure can pose practical challenges due to limited information regarding the marginal damage function and the significant transaction costs involved in developing and managing such a complex scheme. This is particularly true when there are multiple closely substitutable alternatives present.

This study draws upon two pertinent strands of economic literature. First, a body of empirical research investigates the effects of various policy instruments on plastic bag consumption. Prior studies have examined the impacts of existing regulations such as fees or taxes on plastic consumption (e.g., Dikgang et al., 2012; Homonoff, 2018; Mensah, 2021; Homonoff et al., 2021a). These studies suggest that fees and taxes have resulted in reductions in plastic consumption. For instance, Dikgang et al. (2012) documented a notable decrease of 76% in consumer demand for plastic bags in South Africa after the implementation of a levy of 46 rand cents, corresponding to about $0.07 in 2023 value, and with a larger effect immediately after the introduction of the tax. Homonoff (2018) concludes that a $0.05 tax on disposable bag use, corresponding to $0.06 in 2023 value, decreased disposable bag use by over 40%, whereas an equally large subsidy for reusable bags had no significant effects. Results in Mensah (2021) show that a 10% increase in the import tax on plastics leads to a reduction of about 4% and 5% in imports in the short and long run, respectively, while the effects of the simultaneously applied environmental tax on plastics were insignificant.

Other studies investigate the effects of a ban on plastic carrier bags on substitute products. For example, Taylor and Villa-Boas (2016) investigated the repercussions of combining a ban on plastic bags with paper bag fees, revealing a significant decrease in the overall demand for disposable bags. Similarly, Taylor (2019) revealed an unexpected surge in demand for plastic trash bags following the implementation of a ban on plastic carryout bags. Furthermore, recent studies have demonstrated that even modest and incomplete incentives can lead to a reduction in plastic bag consumption. Utilizing data obtained from a national supermarket chain in Uruguay, coupled with advanced impact evaluation statistical methodologies, Cabrera et al. (2021) observed that pricing strategies of US$ 0.07 and US$ 0.10 per unit resulted in a substantial decrease ranging from 70% to 85% in the number of bags used by customers. In a related investigation, He et al. (2023) explored the efficacy of environmentally friendly nudges in mitigating the consumption of single-use cutlery in China. By leveraging detailed customer-level data obtained in collaboration with a food-delivery platform, they reported a remarkable 648% increase in the proportion of orders opting for no-cutlery. Homonoff et al. (2021b) show that in the USA, plastic bag bans have typically led to a boost in the market for substitutes, while general taxation on all disposable bags has led to large decreases in their use as well as their environmental impact. Hence, previous research has not examined how the optimal choice of environmental taxes on disposable bags depends on the choice to jointly or separately tax different bag types. Moreover, the environmental and welfare economic consequences resulting from the choice to optimally regulate one or both markets have not been examined. Such knowledge is important for policymakers who consider applying policy instruments to heterogeneous consumer products.

The second strand of economic literature focuses on the phenomenon of incomplete regulation and leakage, primarily in the context of greenhouse gas emissions (e.g., Fowlie, 2009; Holland, 2012; Fell and Maniloff, 2018), with particular attention to firm-level production decisions concerning input choices (Fullerton and Karney, 2018; Gibson, 2019). However, applications for consumer products such as plastic bags are lacking. This is a weakness because policy instruments targeting consumption choices are common in practice, e.g., to reduce waste, despite being less efficient than environmental taxes directly targeting emissions.

Furthermore, LCA studies have evaluated the environmental impacts of plastics and their alternative substitutes (e.g., Kimmel, 2014; Bisinella et al., 2018; Civancik-Uslu et al., 2019; Ahamed et al., 2021). In particular, Gomez and Escobar (2022) conducted a comprehensive review of LCA studies regarding plastic bags and their potential substitutes, to synthesize recurring conclusions and formulate a methodological framework to guide future studies. Nonetheless, it is noteworthy that the economic ramifications of diverse policy interventions frequently appear to have been overlooked within the purview of LCA investigations.

This study addresses the above-mentioned knowledge gaps by analyzing the environmental and welfare implications of different policy instrument choices concerning plastic bags and their substitutes. The paper contributes to the existing body of research on plastic bag regulations by conducting a comprehensive analysis of the effects of both joint and separate taxation schemes applied to plastic bags and their substitutes, and by assessing the welfare implications associated with these different tax schemes. This paper also contributes to the literature on incomplete regulation and leakage by examining the regulation of consumer products that are close substitutes and may cause multiple environmental externalities. Finally, this study contributes to LCA

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[1] LCA is a comprehensive methodology used to evaluate the environmental impact of a product or activity throughout its entire life cycle.

[2] LCAs of shopping bag alternatives (e.g., plastic, paper, cotton, etc.) have been shown to be sensitive to assumptions made about, for example, the weight, the number of times the bags are used and the end-of-life options.

[3] The Pigouvian tax is an economically optimal levy imposed on producers or consumers involved in activities that generate harmful side effects, so called externalities, for society where these externalities are not otherwise reflected in market prices.

approaches by considering consumers' economic tradeoffs between different carrier bag types.

The subsequent sections of this paper are organized as follows. Section 2 offers a concise overview of the regulatory framework governing plastic packaging, with a specific focus on plastic bags, in both the EU and the United States of America (USA). Section 3 presents the analytical model employed in this study, along with the examination of the first and second-best regulatory solutions. Subsequently, section 4 presents empirical simulations conducted using Denmark as a representative EU Member State and the USA as two distinct case studies. Section 5 engages in a discussion of the results obtained and offers suggestions for potential avenues of future research. The final section presents the conclusion.

2. Plastic bag regulations in the EU and the USA

In 2010, an average EU citizen used 198 plastic carrier bags, implying a total of approximately 100 billion plastic bags (BIO Intelligence Service, 2011). To reduce this, the European Parliament and the European Council adopted Directive (EU) 2015/720 in 2015 concerning the reduction of the consumption of lightweight plastic carrier bags. The two targets set by the directive imply that the consumption of plastic bags should not exceed 90 bags per person per year by the end of 2019, and no more than 40 bags per person per year should be allowed by the end of 2025. As per Eurostat data for the year 2021, the average consumption of lightweight plastic carrier bags per capita in the European Union stood at 77 units, indicating the relative effectiveness of the directive in place.

Additionally, the 2019 Single-Use Plastics Directive strengthens the EU's commitment to reducing the consumption of single-use plastic products in general. Single-use plastic products include a diverse range of commonly used consumer products that are discarded after having been used once for the purpose for which they were provided such as fast-food containers.

To achieve the goals outlined in the directives, Member States are expected to adopt measures to cut consumption. The measures may include national consumption reduction targets; ensuring that reusable alternatives to single-use plastic products are made available at the point of sale to the final consumer; and economic instruments ensuring that single-use plastic products are not provided free of charge at the point of sale to the final consumer. The Member States have the flexibility to choose different policy instruments such as levies and bans.

France and Belgium have banned single-use plastic bags. In Belgium, the Walloon and Brussels regions have banned plastic carrier bags and ultralight bags since 2016 and 2018, respectively. Austria has banned non-biodegradable plastic bags since 2020 as part of a larger action against plastic pollution. In contrast, most EU countries have adopted some form of a levy on plastic bags, where the details are described in Table A1 in Appendix I. The first country to introduce a tax on plastic bags was Denmark in 1993, followed by Ireland in 2002. Studies have shown that plastic bag consumption in both countries has been reduced after the introduction of taxes (Convery et al., 2007).

The 2015 EU directive also mandates that the Member States must report their annual lightweight plastic bag consumption. In 2019, Lithuania, Latvia, and the Czech Republic are the three EU countries with the highest number of lightweight plastic bag consumption per inhabitant (see Fig. A1 in Appendix II). Lithuania consumes on average 331.5 plastic bags per inhabitant and the average number of plastic bags consumed per inhabitant in the EU is 92.8 bags.

A similar development is observed in the USA, where an estimated 103 billion single-use plastic shopping bags were consumed in 2014 (Wagner, 2017). To mitigate the negative consequences of such bags and other single-use plastics, many states have instituted bans and/or fees on items such as plastic bags, carryout containers, polystyrene (Styrofoam), and straws. For example, ten states including California, Colorado, Connecticut, Delaware, Maine, New Jersey, New York, Oregon, Vermont, and Washington have banned single-use plastic bags. Other states such as the District of Columbia and Virginia have enacted legislation requiring all businesses that sell food or alcohol to charge fees for plastic carrier bags. A recent report by Sokolow et al. (2024) revealed that the implementation of single-use plastic bag bans in selected states across the USA leads to an annual reduction of 6 billion such bags. However, they also point out loopholes in the regulations, including the risk of substitution with thicker plastic bags and paper bags.

3. Analytical model

In this section, a simple model is developed for regulating environmental externalities caused by plastic products (x) and their alternative substitutes (y), each having different levels and types of external damage associated with their production and consumption. In particular, the analytical model deals with the efficient design of first- and second-best policy instruments applied to the consumption of plastic products and their substitutes.

3.1. *The first-best solution*

Efficiency requires that regulatory taxes should be levied depending on the external costs of the two products. Thus, the first-best regulation will be materialized if a Pigouvian tax is levied on both plastic bags and their substitute products equivalent to their marginal damage. In this section, the first-best solution is provided, serving as a benchmark for the analysis in later sections.

It is assumed that there are two specific products namely plastic and other grocery bags (e.g., paper bags), that are substitutable in consumption. Plastic bags (x) and other bags (y) are associated with a postulated inverse market demand function $P_i(Q_x, Q_y)$ where P_i is the price for product i (with $i = x, y$) and Q_x and Q_y are the quantity demanded of x and y, respectively. The demand function shows that the quantity demanded of product i is not only determined by its own price but also by the price of the other product, with $\frac{\partial P_i}{\partial Q_i} < 0$ and $\frac{\partial P_i}{\partial Q_j} > 0$ for $i \neq j$.[4] It is assumed that the inverse demand function for each product is derived from a generalized benefit function $B(Q_x, Q_y)$, from which the demand function is obtained as $P_i(Q_x,\ Q_y) = \frac{\partial B(Q_x, Q_y)}{\partial Q_i}$. Next, let c_i represent a constant unit production cost for product i. Production costs of the two products are assumed to be independent of each other, which is reasonable given the fact that the main inputs, fossil fuels and biomass, are different. It is also assumed that the production and supply of both products are competitive.[5]

Let $E(Q_x, Q_y)$, with $\frac{\partial E(Q_x, Q_y)}{\partial Q_i} > 0$, represents the total external (environmental) costs emanating from the consumption of both products. The external costs are assumed to depend on the material characteristics of the two products (for example, degradability and toxicity) as well as the life cycle carbon footprint of the products. In other words, the external costs can be decomposed into two parts: the impact on global warming (through carbon emissions) and marine pollution. Assuming that the impacts on climate and marine ecosystems are additive, the total environmental costs equal the sum of the two impacts.[6]

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[4] It is assumed that income effects are negligible as the expenditures on shopping bags (both plastic and paper bags) are infinitesimal which allows us to focus on substitution effects.

[5] We abstract from the effects of policies on producers' profits, guided by the assumption of a perfectly competitive market wherein profits and producer surplus are deemed negligible, and due to the absence of data pertaining to the supply function.

[6] It is worth noting that marine plastic pollution and greenhouse gas emissions may potentially interact in their impact on marine ecosystems and climate change (Ford et al., 2022). However, the empirical magnitude of these interactions remains unknown.

From the LCA studies, it is observed that the marginal impact of paper bags on climate is higher than plastic bags, whereas the marginal damage of plastic bags on the marine ecosystem is higher than paper bags (Kimmel, 2014; Bisinella et al., 2018; Civancik-Uslu et al., 2019). Indeed, according to a review conducted by Gomez and Escobar (2022), single-use plastic grocery bags emerge as the environmentally preferable option across a majority of assessed scenarios when compared to alternative material categories including paper, cotton, and other polymer variants such as bio-based or oxo-degradable alternatives. Specifically, the single-use plastic bag was found to exhibit approximately 50% of the environmental impact, particularly in terms of climate change, compared to the alternative options under consideration.

Additionally, it is assumed that the regulator aims to maximize social welfare (*SW*) from the use of both plastic and paper bags, i.e., aiming to achieve an efficient level of bag consumption through first-best (if possible) or second-best regulations.

The optimal first-best solution can be found by solving the following objective function.

$$SW = B(Q_x, Q_y) - c_x Q_x \; - c_y Q_y - E(Q_x, Q_y) \tag{1}$$

The first term on the right-hand side of equation (1) represents total benefits, defined as the relevant areas under the inverse demand curves, reflecting the consumer surplus. The next two terms give the total private cost of producing each product defined as the constant unit production cost (c_i) multiplied by the total production. The last term is the total environmental costs.

The first-order conditions (the apostrophes denoting the first-order derivatives) dictate that the respective marginal benefits ($B_x^{'}$ and $B_y^{'}$) should be equal to the sum of marginal private costs of production (c_x and c_y) and marginal external costs[7] ($E_x^{'}$ and $E_y^{'}$).

$$\frac{\partial \mathrm{SW}}{\partial \mathrm{Q_x}} = \mathrm{B_x^{'}} - \mathrm{c_x} - \mathrm{E_x^{'}} = 0 \tag{1a}$$

$$\frac{\partial \mathrm{SW}}{\partial \mathrm{Q_y}} = \mathrm{B_y^{'}} - \mathrm{c_y} - \mathrm{E_y^{'}} = 0 \tag{1b}$$

Now, the generalized optimal price of product *i* in the presence of externality can be defined as the constant unit production cost c_i plus a tax payment t_i, and the equilibrium conditions are such that the marginal benefits are equalized to this price for each product $\frac{\partial B(Q_x, Q_y)}{\partial Q_x} = c_x + t_x$ and $\frac{\partial B(Q_x, Q_y)}{\partial Q_y} = c_y + t_y$. The first-order conditions imply that social welfare will be maximized if both products are taxed exactly the amount of their marginal external costs i.e., $t_x = E_x^{'}$ and $t_y = E_y^{'}$.

3.2. Second-best solutions

In this section, we examine different second-best regulations, including taxing only one of the products independently and a common uniform tax policy for both products. Throughout this analysis, we assume that the regulatory body aims to maximize social welfare associated with the consumption of the two types of bags.

3.2.1. Taxing only one of the products

Drawing on Small and Verhoef (2007), Verhoef et al. (1996) and Verhoef et al. (1995, a simple model is constructed for optimal taxation of only a single product in the presence of a substitute product, considering a situation where both products give rise to environmental externalities. More specifically, the regulator's objective is to find an optimal tax for plastic bags (τ_x) that maximizes social welfare with the constraint that the tax on paper bags is fixed at zero.

The maximization problem shares similarities with the above first-best problem, but two restrictions have now been added. The first restriction states that the market for plastic bags must be in equilibrium when the tax τ_x is introduced, i.e., the price in the presence of the tax must equal the marginal cost of production:

$$B_x^{'} - \tau_x = c_x \tag{2}$$

The second restriction states that the market for paper bags must also be in equilibrium. As the tax on paper bags is constrained to zero, the market equilibrium can simply be expressed as:

$$B_y^{'} = c_y \tag{3}$$

Using the objective function in equation (1) together with equations (2) and (3), the optimal single-product tax can be found by solving the following Lagrangian:

$$\begin{aligned} L = B(Q_x, Q_y) - c_x Q_x \; - c_y Q_y - E(Q_x, Q_y) + \lambda_x \left[B_x^{'} - c_x - \tau_x\right] \\ + \lambda_y \left[B_y^{'} - c_y\right], \end{aligned} \tag{4}$$

where the variables λ_i give the shadow price of the equilibrium constraint for product *i*. In other words, the Lagrange multipliers λ_x and λ_y reflect the marginal impact of a relaxation of the associated constraint upon the optimized value of the objective. This implies that the equilibrium value of λ_i should give the impact on the social benefits of a marginal increase in a tax on product *i*. Therefore, it is expected to find $\lambda_x = 0$ in the second-best optimum (as τ_x should be set optimally) and $\lambda_y < 0$ when paper bags also cause environmental damage (since the benefit would be increased if a tax could be included in the second constraint). The first-order conditions to equation (4) confirm this:

$$\frac{\partial L}{\partial Q_x} = B_x^{'} - c_x - E_x^{'} + \lambda_x B_{xx}^{''} + \lambda_y B_{yx}^{''} = 0, \tag{4a}$$

$$\frac{\partial L}{\partial Q_y} = B_y^{'} - c_y - E_y^{'} + \lambda_x B_{xy}^{''} + \lambda_y B_{yy}^{''} = 0 \tag{4b}$$

$$\frac{\partial L}{\partial \lambda_x} = B_x^{'} - c_x - \tau_x = 0 \tag{4c}$$

$$\frac{\partial L}{\partial \lambda_y} = B_y^{'} - c_y = 0 \tag{4d}$$

$$\frac{\partial L}{\partial \tau_x} = \lambda_x = 0 \tag{4e}$$

The first-order conditions in equations (4a) and (4b) differ from equations (1a) and (1b), in that equations (4a) and (4b) show that in equilibrium the marginal benefit ($B_x^{'}$) should not only be equal to the marginal costs plus the direct marginal damage but should also take into account the change in damage due to the spillover effects of the unilateral plastic tax.

Using equations (4a), (4c) and (4e), it is found that:

$$\mathrm{\tau_x} = \mathrm{E_x^{'}} - \mathrm{\lambda_y B_{yx}^{''}}$$

Using equations (4b) and (4d) and solving for λ_y yields:

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[7] For tractability, the analysis (especially in the empirical part) is simplified by assuming that the marginal external costs (damages) are constant. This assumption is frequently made when studying a global pollutant, such as greenhouse gas emissions, where the individual country does not significantly affect the overall pollution level. Moreover, the same assumption is plausible when a particular emission source makes a relatively small contribution to a given pollution problem, which applies to paper bags' contribution to nutrient pollution of the marine environment, where agriculture and wastewater treatment plants are the main sources. In the case of plastic bags' impact on the marine environment, this assumption should be seen as a simplification, motivated by the limited availability of data.

$$\lambda_y = \frac{E'_y}{B''_{yy}}$$

Substitution of λ_y then yields the optimal second-best unilateral tax on plastic bags alone:

$$\tau_x = E'_x - E'_y \frac{B''_{yx}}{B''_{yy}} \tag{5}$$

Thus, the tax on plastic bags is equal to the marginal environmental cost of plastic bags, minus a certain fraction of the marginal environmental cost of paper bags. The first term on the right-hand side in equation (5) is the marginal external environmental costs of plastic bags. The second term ($-E'_y\frac{B''_{yx}}{B''_{yy}}$), which is negative, captures the tax's indirect spillover effect on paper bags through induced substitution. Equation (5) shows that when the y good, i.e., paper bags, is a substitute for the x good, i.e., plastic bags, a unilateral tax on plastic bags would be lower than in the Pigouvian case. The intuition behind this result is that setting a tax on plastics leads to a substitution for paper bags. The increase in paper bag consumption leads to additional environmental externalities. The magnitude of the effect depends on three factors: the marginal environmental damage costs of paper bags, E'_y; the strength of the substitution effect, B''_{yx}; and the slope of the demand curve for paper bags, B''_{yy}. The strength of the substitution effect, B''_{yx} (which can also be considered as the cross-price elasticity of demand) affects τ_x negatively i.e., the stronger the substitution effect, the lower τ_x will be. On the other hand, the slope of the demand curve for paper bags (B''_{yy}) has a positive effect i.e., the steeper the slope of the demand for paper bags, the higher the τ_x will be, because the leakage effect is then lower. Moreover, the higher marginal environmental damage costs of paper bags, E'_y, will decrease τ_x. To further interpret equation (5), three extreme cases could be considered. First, if the two goods were unrelated (i.e., if B''_{yx} were zero), τ_x will equal the marginal environmental damage costs of plastic bags, E'_x, i.e., equal to the Pigouvian tax. Second, if the marginal environmental damage costs of paper bags were negligible (i.e., $E'_y \sim 0$), again τ_x will be just the Pigouvian tax. Finally, if the demand for paper bags is perfectly inelastic (i.e., $B''_{yy} = -\infty$), τ_x will also equal the Pigouvian tax.

3.2.2. *Applying a common uniform tax*

Now, suppose that the regulatory body wants to improve welfare by utilizing another second-best regulation: an undifferentiated tax policy. The objective of the regulator is still defined by equation (1), and the market restrictions in equations (2) and (3) apply. An additional restriction is included for the tax to be uniform across the two markets, i.e.:

$$\tau_y = \tau_x = \tau. \tag{6}$$

The optimal common fee can then be found by solving the following Lagrangian:

$$L = B(Q_x, Q_y) - c_x Q_x - c_y Q_y - E(Q_x, Q_y) + \lambda_x\left[B'_x - c_x - \tau\right] + \lambda_y\left[B'_y - c_y - \tau\right]. \tag{7}$$

The first-order conditions for this problem are as follows:

$$\frac{\partial L}{\partial Q_x} = B'_x - c_x - E'_x + \lambda_x B''_{xx} + \lambda_y B''_{yx} = 0, \tag{7a}$$

$$\frac{\partial L}{\partial Q_y} = B'_y - c_y - E'_y + \lambda_x B''_{xy} + \lambda_y B''_{yy} = 0, \tag{7b}$$

$$\frac{\partial L}{\partial \lambda_x} = B'_x - c_x - \tau = 0, \tag{7c}$$

$$\frac{\partial L}{\partial \lambda_y} = B'_y - c_y - \tau = 0, \tag{7d}$$

$$\frac{\partial L}{\partial \tau} = -\left(\lambda_x + \lambda_y\right) = 0. \tag{7e}$$

The first-order conditions in equations (7a)-(7e) have similarities to equations (4a)-(4e), with the exception that both λ_x and λ_y now take non-zero values. The parameters λ_x and λ_y cause these first-order conditions to differ from the first-best optimal ones. In the context of equation (7), where the common fee τ is substituted with a differentiated tax t_i, the first-order conditions entail the requirement that $\lambda_i = 0$ for both x and y. Hence, the first best optimum is given by $t_i = E'_i$ which are the standard Pigouvian taxes equal to marginal external costs. In the second-best case with a uniform tax, however, equations (7a), (7b), and (7e) imply the following expressions for λ_x and λ_y:

$$\lambda_x = \frac{-\left(E'_x - E'_y\right)}{\left(B''_{xy} - B''_{yy}\right) - \left(B''_{xx} - B''_{yx}\right)}, \tag{8}$$

$$\lambda_y = \frac{E'_x - E'_y}{\left(B''_{xy} - B''_{yy}\right) - \left(B''_{xx} - B''_{yx}\right)}, \tag{9}$$

Using equations (7c) and (7d) together with the expressions for the lambdas gives the following simplified expression for the optimal uniform tax:

$$\tau = E'_x \frac{A}{A - Z} - E'_y \frac{Z}{A - Z} \tag{10}$$

where $A = (B''_{xy} - B''_{yy})$ and $Z = (B''_{xx} - B''_{yx})$. Equation (10) shows that the optimal common tax is a weighted average of the marginal environmental costs of the two goods. The level of the uniform tax will be lower than the Pigouvian tax on plastics if the marginal external damage from plastic bags is larger than the marginal external damage from paper bags. A detailed interpretation is provided in Appendix III.

4. Empirical simulation

In this section, empirical simulations are conducted using Denmark and the USA as case studies to analyze the outcomes predicted by the analytical model. The selection of these countries is primarily based on data availability, and Denmark is particularly noteworthy as it was the first country to implement plastic bag taxes within the EU.

4.1. *Bag demand and supply functions*

The empirical simulations are conducted based on the assumption that the demand functions for both plastic bags (x) and paper bags (y) can be represented by linear equations[8]:

$$Q_x = a_0 + a_1 P_x + a_2 P_y \text{ and } Q_y = b_0 + b_1 P_y + b_2 P_x \tag{11}$$

where the coefficients a and b are associated with the demand for plastic bags and paper bags, respectively. Specifically, $a_1 < 0$ and $b_1 < 0$ represent the own price effects on the quantity demanded for each product, while $a_2 > 0$ and $b_2 > 0$ indicate the cross-price effects of the prices of the other product. The estimation of these coefficients is based on the definition of own and cross-price elasticities of demand for both

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[8] The assumption of linear demand function is common practice in empirical economic analysis.

products as follows:

$$a_1 = \varepsilon_x \cdot \frac{Q_x}{P_x}\ ;\ a_2 = \varepsilon_{xy} \cdot \frac{Q_x}{P_y}\ ;\ b_1 = \varepsilon_y \cdot \frac{Q_y}{P_y}, \text{and } b_2 = \varepsilon_{yx} \cdot \frac{Q_y}{P_x} \tag{12}$$

where Q_x and Q_y represent the annual consumption levels of plastic and paper bags respectively, while P_x and P_y represent their respective annual mean prices. The own-price elasticities of demand are denoted as ε_x and ε_y while ε_{xy} and ε_{yx} denote the cross-price elasticities of demand.

By substituting the specific values of the coefficients a's and b's from equation (12) into their respective demand functions in equation (11) and solving for the intercepts, the following results are obtained.

$$\mathrm{a}_0 = \mathrm{Q}_\mathrm{x}\left(1\text{-}\varepsilon_\mathrm{x}\text{-}\varepsilon_\mathrm{xy}\right) \text{ and } \mathrm{b}_0 = \mathrm{Q}_\mathrm{y}\left(1\text{-}\varepsilon_\mathrm{y}\text{-}\varepsilon_\mathrm{yx}\right)$$

For the analysis, price elasticities of demand estimated by Zhang and Buongiorno (1998) were relied upon, along with data on the annual consumption of plastic and paper bags from Wagner (2017) and personal communication from the Danish Environmental Protection Agency. Additionally, prevailing market prices for plastic and paper bags were utilized to derive the parameters of the demand functions specified in equation (11) for both products in the USA and Denmark.

Zhang and Buongiorno (1998) conducted a study in the USA where they estimated the own and cross-price elasticities of demand for plastic and paper packaging. Their approach involved employing two-stage expenditure share equations to model packaging consumption. In the first stage, consumers were assumed to maximize utility while adhering to a budget constraint when choosing the amount of packaging, including paper and plastic, as well as other goods and services. The second stage involved allocating packaging expenditure between paper and plastic packaging. By utilizing a seemingly unrelated regression model with annual data spanning from 1960 to 1991, conditional elasticities were calculated. Given the absence of an equivalent study for Denmark, it is assumed that the price elasticities of demand for Denmark are equivalent to those estimated for the USA.

According to data from the Danish Environmental Protection Agency, the estimated average consumption of plastic bags in Denmark between 2017 and 2020 is approximately 373 million. As for paper bags, the estimated consumption in Denmark is around 87 million. In comparison, the USA has a significantly higher consumption of bags, with estimated totals of 103 billion plastic bags and 10 billion paper bags annually (Wagner, 2017). In terms of prices, the mean price of plastic bags in Denmark is estimated to be \$0.57 per bag (around 4 DKK), while the mean price of paper bags is estimated to be \$0.71 (around 5 DKK) per bag.[9] In the USA, the assumed mean prices for plastic and paper bags are lower, equaling \$0.38 and \$0.43 per bag, respectively[10]. Table 1 presents the relevant data on the price elasticity of demand, including associated standard errors, as well as the quantities and prices of plastic and paper bags for both Denmark and the USA.

The demand functions for plastic and paper bags in Denmark (DK) and the USA can be expressed as follows (quantities are measured in billions):

$$Q_{x_{DK}} = 0.768 - 0.798P_x + 0.084P_y \text{ and } Q_{x_{USA}} = 212 - 330.7P_x + 38.3P_y$$

$$\mathrm{Q}_{\mathrm{y}_{\mathrm{DK}}} = 0.124 - 0.072\mathrm{P}_\mathrm{y} + 0.024\mathrm{P}_\mathrm{x} \text{ and } \mathrm{Q}_{\mathrm{y}_{\mathrm{USA}}} = 14.3 - 13.7\mathrm{P}_\mathrm{y} + 4.2\mathrm{P}_\mathrm{x}$$

Moreover, information obtained from the plastics industry suggests that the production cost of a plastic grocery bag is approximately one penny (\$0.01), while a paper bag costs around 4 or 5 cents (\$0.04-\$0.05) per bag. These production costs serve as inputs in the model and are considered part of the supply function.

Table 1
Data for the calculation of demand function parameters.

	Plastics bags		Paper bags	
	USA	Denmark	USA	Denmark
Own price elasticity of demand	$\varepsilon_x =$ -1.22		$\varepsilon_y =$ -0.59	
The cross-price elasticity of demand[a]	$\varepsilon_{xy} =$ -0.56		$\varepsilon_{yx} =$ 0.16	
Consumption of bags per year (in billions)	103	0.373	10	0.087
Average price per bag (in US dollars)	0.38	0.57	0.43	0.71

[a] The cross-price elasticities of demand reported by Zhang and Buongiorno (1998) are non-symmetrical and of opposite signs. Only the positive estimate, $\varepsilon_{yx} = 0.16$, is used, as accurate calculations of welfare impacts require symmetry. Moreover, it is not obvious that income effects would differ substantially between the different bag types which could otherwise motivate non-symmetrical cross-price elasticities.

4.2. *Environmental damage costs*

The assessment of environmental damage costs in this study encompasses two external costs associated with the consumption of plastic and paper carrier bags: the estimated costs on the marine ecosystem and climate change.

4.2.1. *The marginal damage of plastic bags to the marine environment*

Plastics are a stock pollutant, accumulating over time in the marine environment. To calculate the marginal damage of plastic bag consumption, it is necessary to identify the marginal damage of plastic bags that reach the sea as well as the share of plastic bags ending up in the ocean. Thus, it is important to understand how long the plastic remains in the sea, and what economic damage is caused by the plastics in the sea. For this purpose, the assessment in Beaumont et al. (2019) is utilized, which estimates the annual damage of the global stock of marine plastic pollution in 2011, based on the impact of plastics on a large range of ecosystem services. First, they carry out a systematic review of the impact on ecosystem services, showing that this impact is substantial and negative for almost all ecosystem services on a global scale. Based thereon, they judge that it is reasonable to assume a 1–5% reduction in marine ecosystem service delivery because of the stock of marine plastic in the oceans in 2011. Next, they use data on aggregate global benefits provided to society by marine ecosystem services using results from Costanza et al. (2014)which show that these benefits sum to approximately \$49.7 trillion per year. The 1–5% decline in marine ecosystem service delivery then implies an annual loss of \$500–\$2500 billion from plastic in the marine environment. Each ton of plastic in the ocean would then, on average, cause annual damage (AD^S) of between \$3300 and \$33,000 (Beaumont et al., 2019). It is assumed that these figures serve as an indicator of the plausible range of marginal damage from plastic in the ocean. This is, of course, a simplification, as in reality, the marginal damage will depend on the location of the plastic in the ocean, the size of the stock, and the type of plastic.

Next, the marginal damage that accrues from one unit of emissions of plastic bags to the sea needs to be identified. To calculate that, information on the decay rate of plastic bags and the discount rate are required. The decay rate is calculated based on estimates of the half-life of plastic bags in the marine environment, which is estimated to be 3.4–5 years, where the former figure applies when the plastic is exposed to a degradation accelerant such as UV or high temperatures (Chamas et al., 2020). The mean of the two figures is used, and assuming an exponential decay function, the annual decay rate then equals 0.17. Furthermore, a social discount rate equal to 3.5 percent is assumed, as suggested by Moore et al. (2013). Then, the marginal damage of emissions (i.e., of plastic bags entering the ocean), MD^E, is calculated as the

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[9] The prevailing market prices (in 2022) for plastic and paper bags in Danish supermarkets.

[10] The prices are taken from the website of Amazon USA (the price of plastic bags of similar quality as plastic bags available in Danish supermarkets).

net present value of the damage that accrues over the first 100 years, using the formula $MD^E = \sum_{t=0}^{100} AD^S(1-\rho)^t/(1+r)^t$, where AD^S is the annual marginal damage of the stock, ρ is the decay rate, r is the discount rate, and t is the year. This gives marginal damage of emissions ranging between $19,671 and $196,712 per ton of plastic bags entering the ocean. The average of the two figures ($108,192) is used as a baseline for the calculations. In the sensitivity analysis, results are compared across the whole range of marginal damage estimates.

On average, the typical weight of a single plastic carrier bag is approximately 10 g. Consequently, it can be inferred that an approximate quantity of 100,000 plastic bags would constitute a metric ton of plastic waste. This relationship establishes the basis for evaluating the marginal cost of environmental damage associated with plastic bags that have entered the marine ecosystem, which is estimated to amount to $1.08 per bag. However, it is important to note that not all plastic bags that are used end up in the marine environment; rather, only a fraction of the total consumption of plastic bags ultimately finds its way into marine ecosystems. Therefore, to assess the expected marginal damage per purchased plastic bag, it is necessary to consider the probability of a bag entering the marine environment, a parameter referred to as the "littering rate" (γ). According to estimates provided by TheWorldCounts, it is suggested that approximately 10% of the plastic bags consumed ultimately enter the marine environment. Taking this into account, the resulting marginal environmental cost per purchased plastic bag can be calculated to be $0.108.

4.2.2. The marginal damage of paper bags to the marine environment

To assess the environmental damage caused by paper bags to both marine and freshwater ecosystems, LCA studies that provide insights into pollution emissions associated with such bags are relied upon. Additionally, studies that estimate the cost of damage caused by different types of pollutants are considered. To quantify the emissions associated with paper bags, the study conducted by Bisinella et al. (2018), offers a comprehensive evaluation of the environmental impacts resulting from the use of grocery bags is used. According to their findings, a bleached craft paper bag is estimated to emit approximately 1.7E-05 kg of phosphorus equivalents and 1.4E-04 kg of nitrogen equivalents. To estimate the marginal social damage cost associated with nitrogen emissions, the study by Brink et al. (2011) is used. Their research suggests that the cost ranges between €25 and €102 per kilogram of nitrogen emission within the EU context. Furthermore, Gourevitch et al. (2021) estimated the marginal abatement cost of phosphorus to be approximately $934 per kilogram. It is important to acknowledge that these estimates are simplified approximations. The actual marginal damage and abatement costs will vary depending on the specific characteristics of water bodies and the levels of eutrophication present in different marine and freshwater environments. Using the figures provided in the above-mentioned studies, it is estimated that the marginal marine environmental damage cost attributed to paper bags, due to nitrogen and phosphorus emissions, ranges between $0.014 and $0.034 per bag.

4.2.3. Climate change impacts

The monetary damage costs associated with the consumption of plastic and paper bags concerning climate change are calculated by multiplying the social cost of carbon by the CO2-equivalent emissions per bag. To estimate the climate change impacts of both types of bags, once again the findings of LCA studies are referred to. These studies provide estimates of the carbon emissions, expressed in CO2 equivalents, resulting from the production and use of one unit of plastic and paper bags. Table 2 presents a summary of selected LCA studies conducted in various countries, which estimate CO2 emissions for both plastic and paper bags. Among these studies, the CO2 emission values per bag reported by Bisinella et al. (2018) are utilized as they are considered to be the most robust and comprehensive. The selection of this particular study is justified based on the rigorous methodologies and considerations discussed earlier.

In 2021, the Interagency Working Group on Social Cost of Greenhouse Gases within the US government established an estimated social cost of carbon (SCC) at approximately $51 per metric ton of CO2. This value reflects the anticipated SCC considering uncertainties related to climate warming response, economic growth scenarios, and population projections. Wang et al. (2019) conducted a meta-analysis based on peer-reviewed studies and reported a range of SCC estimates from −13.36 to 2386.91 dollars per metric ton of CO2, with a mean value of $54.7 per metric ton of CO2. Rennert et al. (2021) further refined the estimation made by the Interagency Working Group by employing alternative approaches, including non-probabilistic scenarios and constant discounting. Their estimates ranged from $56.2 to $785 per metric ton of CO2, depending on the discounting method, discount rate, and assumptions about uncertainty distribution. For the analysis, the arithmetic mean derived from estimations provided by Rennert et al. (2021), which were averaged across eight different scenarios, is employed. Consequently, the mean SCC is calculated to be $0.227 per kilogram of CO2.

Based on these SCC estimates, the marginal damage costs attributed to the consumption of plastic and paper bags concerning climate change are determined. Specifically, the marginal damage cost per bag is estimated to be $0.025 for plastic bags and $0.041 for paper bags. To provide a comprehensive overview of the empirically estimated damage costs, Table 3 presents a summary of these values, which will be utilized to calculate the corresponding tax rates.

Table 3
Summary of marine and climate damage costs of plastic and paper bags.

Cost item	Costs (in $) per purchased bag	
	Plastic bags	Paper bags
Damage costs to marine pollution	0.108	0.024
Damage costs to climate change	0.025	0.041
Summation of damage costs	*0.133*	*0.065*

Table 2
Estimated CO_2 emissions per bag for plastic and paper bags.

Study	Country	CO_2 emission kilogram equivalents		Remarks
		Plastic	Paper	
Civancik-Uslu et al. (2019)	Spain	9.32	29.5	Single-use
Bisinella et al. (2018)	Denmark	0.11	0.18	End-of-life (incineration)
Greene (2011)	USA	0.04	0.08	
Edwards and Meyhoff Fry (2011)	UK	2.1	5.4	
Muthu et al. (2011); (2012)	China and India	50	200	in 20 Years

Table 4
Sensitivity analysis on welfare change.

Parameters	Annual Welfare Gain (in billions of $)			
	USA		Denmark	
	A tax only on plastic bags	A common uniform tax	A tax only on plastic bags	A common uniform tax
Baseline	2.91	2.93	0.0069	0.0071
Half-life (3 years)	1.49	1.53	0.0035	0.0038
Half-life (50 years)	21.13	20.91	0.0670	0.0631
Marginal damage of stock (at min. level of $3300)	0.3206	0.3494	0.00074	0.0009
Marginal damage of stock (at max. level of $33,000)	8.09	8.02	0.0194	0.0191
Littering rate (at min level 5%)	1.02	1.06	0.0024	0.0026
Littering rate (at max level 80%)	46.19	43.52	0.1685	0.1542

4.3. *Results*

This section provides an analysis of the tax rates derived from the data presented in Table 4, employing equations (5) and (10). Additionally, an assessment of the welfare implications associated with these various tax rates will be presented.

4.3.1. *First and second-best environmental taxes*

Given the assumption of constant marginal damage, equal across various geographic locations, the optimal Pigouvian taxes for plastic and paper bags are derived as the summation of different marginal damage incurred by each product. The resulting taxes are estimated to be $0.1332 and $0.0646 per bag for plastic and paper bags, respectively, indicating that the optimal Pigouvian tax on plastic bags is twice as high as that on paper bags.[11]

To calculate the second-best taxes, the direct demand functions are transformed into their inverse forms, and the parameters from these inverse demand functions are inserted in equations (5) and (10). The relevant inverse demand equations are provided in Appendix IV. It is important to note that the second-best taxes differ between the USA and Denmark, owing to differences in the slope of the demand functions for plastic and paper bags across the two countries.

Fig. 1 shows the three different tax rates. The Pigouvian tax on plastic bags is higher than the other two tax rates. The single tax on plastic bags is lower than the Pigouvian tax on plastics because this tax considers the spillover effect on paper bag use. The common uniform tax rate is lower than the other two tax rates. The intuition is that the common uniform tax rate is the weighted average of the marginal damage of the two bag types and therefore the level is between the Pigouvian taxes for plastic and paper bags. As can be seen in the figure, the variation in tax level across the studied scenarios is small for default parameters.

The second-best tax rates in the United States are slightly higher in comparison to those observed in Denmark. This can be attributed to differences in the demand functions for plastic and paper bags between the two countries. In the context of a singular tax imposed on plastic bags, the key determinant is the relative magnitude of the substitution effect and own price effect on paper bags, denoted as $(\frac{B''_{yx}}{B''_{yy}})$. This ratio is larger in Denmark, signifying a higher propensity among consumers to replace plastic bags with paper bags, thereby amplifying the spillover effect. This underscores the significance of analyzing the own and cross-price elasticities of plastic and paper bags, the values of which may vary across different countries. Although it is challenging to determine the magnitude of the common uniform tax conceptually, the empirical results show that this tax rate is also higher in the USA.

4.3.2. *Welfare effects*

Next, the welfare effects of the different tax regimes are calculated as compared to a scenario where there are no taxes. The net welfare change comprises two elements: a change in consumer surplus because of the price changes caused by the introduction of taxes, and a change in environmental damage because of the change in the consumption pattern of the goods. The indirect demand functions are used to assess the welfare changes on consumer surplus following Araar and Verme (2019) (see Appendix V for details).

Fig. 2 **(a)** and **(b)** portray the net welfare effects of the first-best solution (Pigouvian taxes) and the two second-best taxes (a common uniform tax and a singular tax solely on plastic bags) for both the USA and Denmark. Comparing the two second-best taxes, the findings show that a common uniform tax on plastic and paper bags may lead to a relatively higher net welfare gain compared to a singular tax solely imposed on plastic bags. Intuitively, the reason is that the common tax takes into account further information on the simultaneous consumer responses in the two markets, compared to the singular tax on plastic bags. It is noteworthy that the tax exclusively directed at plastic bags results in the least consumer surplus loss; however, it also leads to the least reduction in environmental damage. Consequently, these opposing effects contribute to the lowest net welfare gain associated with this tax in both countries.

The highest net welfare gain would be achieved by implementing the Pigouvian taxes on both plastic and paper bags, resulting in a $2.96 billion welfare gain per year for the USA (equivalent to approximately $8.82 per capita) and $7.23 million for Denmark (equivalent to approximately $1.22 per capita) per year. The reason for the notably greater gross welfare changes in the United States is the larger magnitude of demand for plastic and paper bags within the country. Furthermore, the per capita welfare gain is also more substantial in the United States and is likely due to the low current market prices on plastic and paper bags that fail to account for the external environmental costs. Consequently, the introduction of either one of the three tax types would serve to increase the welfare gain, due to the reduction in environmental damage.

4.4. *Sensitivity analysis*

The calculations of the various tax rates and their welfare impacts, as illustrated in Figs. 1 and 2, rely on a set of underlying assumptions, as described earlier. To assess and compare the significance of these assumptions, a sensitivity analysis is conducted that focuses on the most

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[11] In the context of environmental externalities that vary and are not fixed per unit of output, the optimal Pigouvian policy would directly target the pollution itself. However, in the calculation of the "Pigouvian" tax rate, certain assumptions have been made, such as the assumption that all used bags will not end up in the marine environment. These assumptions may result in the calculated tax rate deviating from the true first-best solution. Nevertheless, throughout this paper, this tax rate is consistently referred to as the "first-best" solution to distinguish it from the other alternative second-best taxes.

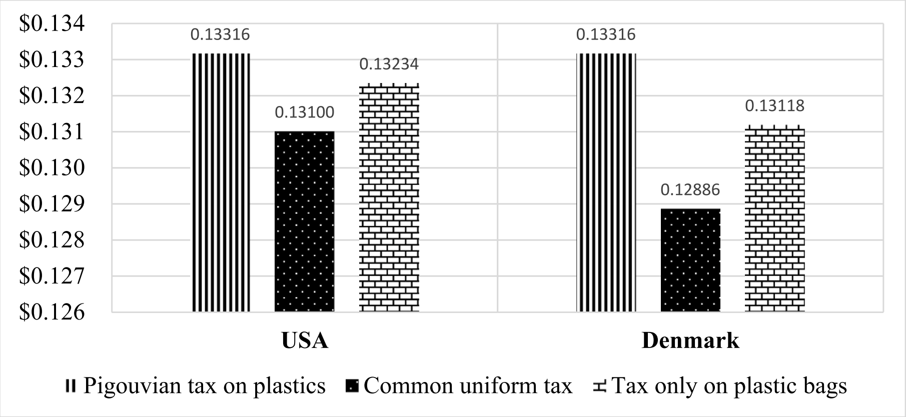
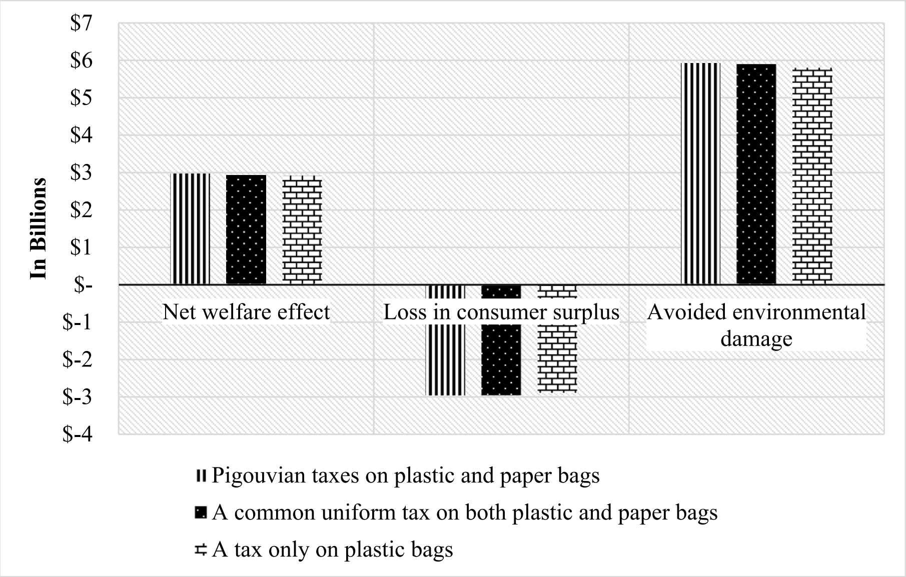
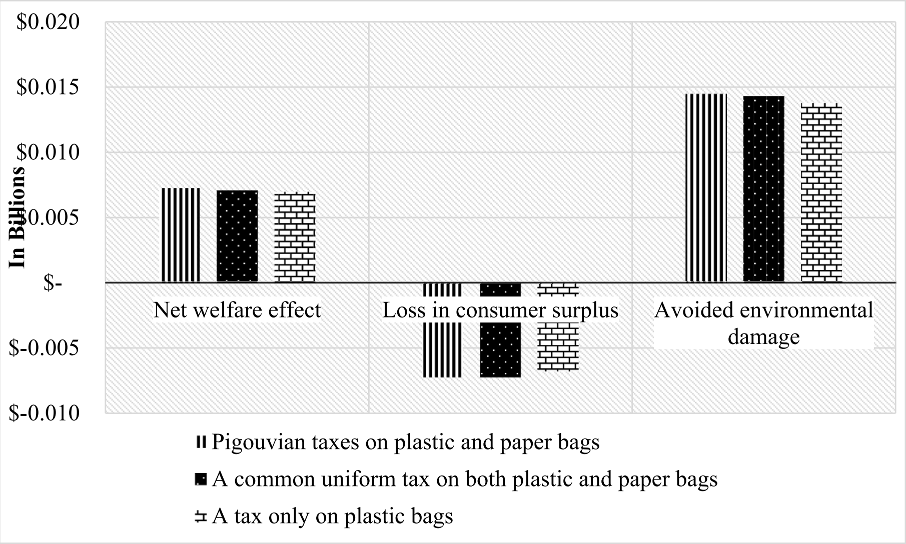


Fig. 1. Magnitudes of first and second-best taxes.

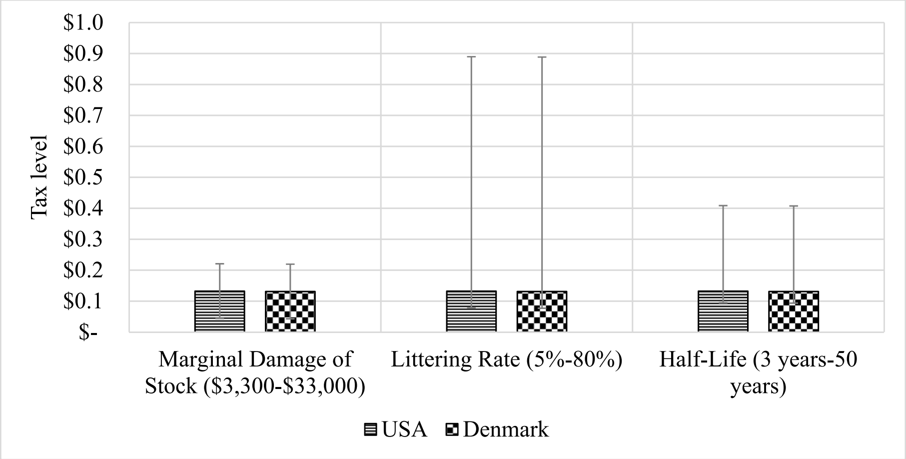


(a) USA

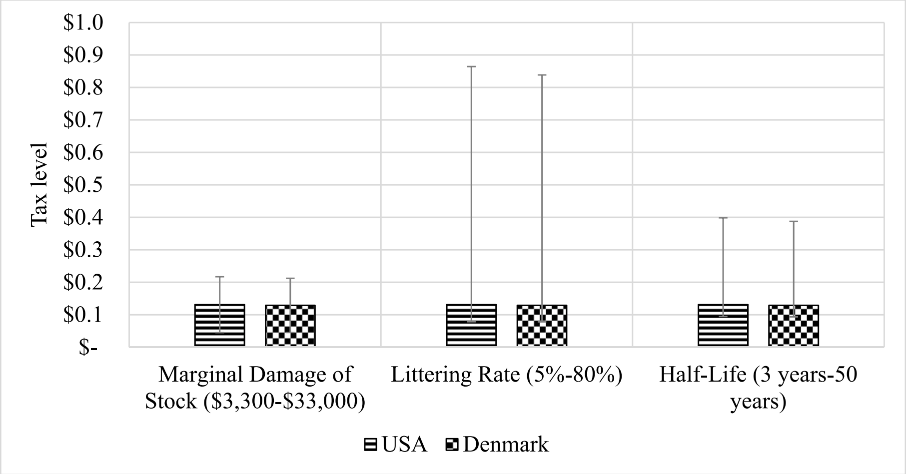


(b) Denmark

Fig. 2. The welfare effects of first and second-best taxes.



(a) Sensitivity analysis for the tax only on plastic bags.



(b) Sensitivity analysis for the common uniform tax.

Fig. 3. Sensitivity analysis on the magnitude of the tax rates.

critical parameters[12] within the empirical model: the damage cost of the stock of plastic pollution, ranging from $3300 to $33,000 (Beaumont et al. (2019), the half-life of plastic bags, ranging from 3 years to 50 years (Chamas et al., 2020), and the percentage of plastic bags entering the marine environment, i.e., the littering rate, ranging from 5% to 80%. Despite the relatively low incidence of littering in both the USA and Denmark, it is essential to undertake a sensitivity analysis to account for the significant disparities in littering rates across diverse countries, particularly between developed and developing nations.

Fig. 3 **(a)** and **(b)** present the results of the sensitivity analysis on the magnitudes of the two tax rates with respect to the three parameters. The findings highlight the considerable influence of the decay and littering rates on the tax rate values. For instance, when the half-life of plastics is extended from 3 years to 50 years (a factor of 16.7), both the tax solely on plastic bags and the common uniform tax would increase approximately fourfold. Conversely, if the littering rate rises from 5% to 80% (a factor of 16), all tax rates would increase approximately eightfold. The sensitivity simulations show that the tax solely on plastic bags remains higher than the common uniform tax. However, in scenarios with lower environmental damage values, such as under a littering rate of 5%, the lower bounds of taxing only plastic bags may be less than that of the common uniform tax.

The sensitivity analyses conducted with respect to the three parameters shed light on the potential welfare implications of the different tax scenarios. Specifically, when the decay rate of plastic bags is exceptionally low (e.g., a half-life of 50 years, indicating a decomposition period exceeding 500 years), or the littering rate of plastic bags in the marine environment is high (such as around 80%), high tax rates can be justified. In extreme scenarios characterized by a very low decay rate and a very high littering rate , the imposition of a very high tax rate on plastic bags may effectively work as a ban on plastic bags, as consumption becomes zero, i.e., the new price with the price including the tax exceeds the consumers' maximum willingness to pay. Thus, with a very high environmental impact of plastic bags a complete ban could be a viable option, in particular as the taxation approach would result in an exorbitantly high rate and price that could potentially face significant political resistance. Conversely, if the decay rate is high or the percentage of litter entering the marine environment is low (e.g., a littering rate below 5%), the imposition of high tax rates or a ban on plastic bags could result in a significant welfare loss.

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[12] We also conducted sensitivity analyses with respect to price elasticities of demand and the prevailing market prices, varying them by ±20% of their values, but found no discernible effect on the magnitude of taxes or the ranking of different tax schemes in terms of their impact on welfare.

Table 4 provides an overview of the summary of the results derived from the sensitivity analysis conducted to assess changes in welfare. The sensitivity analysis systematically examined the minimum and maximum values of pertinent parameters, contrasting them with the baseline estimations computed using average parameter values. While the sensitivity analysis on the magnitudes of the tax rates shows that the singular tax solely on plastic bags is higher in most scenarios (as shown in Fig. 3), the potential welfare gains exhibit variability contingent upon the assumptions underpinning the diverse parameters. Specifically, when considering scenarios in which the half-life of plastics extends to 50 years or when the littering rate reaches 80%, a tax exclusively targeting plastic bags proves more advantageous in terms of welfare gain when compared to a common uniform tax.

5. Discussion

The present study evaluates the first-best and two second-best regulatory solutions for addressing the environmental externalities associated with shopping bags made of plastic and paper. These materials have different environmental profiles, and the ongoing debate surrounding their relative impact has attracted significant attention, particularly concerning marine pollution. Media outlets have played a prominent role in shaping public perception, emphasizing the adverse effects of plastic bags on marine ecosystems (for example, BBC, 2019; NYT, 2019; Forbes, 2020; DR, 2021). In line with that, several empirical findings suggest that consumers tend to perceive plastics as more environmentally harmful (see e.g., Boesen et al., 2019; Steenis et al., 2017; Lindh et al., 2016), possibly influenced by frequent media coverage (Stafford and Jones, 2019a, 2019b), despite the actual environmental impact of these materials. Consequently, many countries have implemented bans or taxes solely on plastic bags. However, as concluded in a review of LCA studies by Gomez and Escobar (2022), the outright exclusion or prohibition of single-use plastic grocery bags may not be warranted, as they have been identified as potentially the most environmentally friendly option across numerous scenarios when compared to other alternatives mentioned above. Moreover, plastic bags offer advantages to consumers due to their waterproof and hygienic properties, facilitating the safeguarding of moisture-sensitive and perishable items. Such attributes are deemed critical from both economic and health perspectives.

The academic literature has lacked formal economic analyses, especially regarding the interplay between shopping bag demand and the welfare effects of various policy tools. The contribution of this paper to the existing literature consists of an examination of first-best and second-best regulatory solutions (i.e. taxation) while accounting for the spillover effects of policies targeting different bag materials and the trade-offs between marine pollution and climate change externalities.

The simulation results of this study indicate that Pigouvian taxes on plastic bags are approximately twice as high as those on paper bags, reflecting the higher environmental cost associated with plastics. This aligns with the prevalent emphasis on plastic bag taxation in many countries. However, the simulations suggest that a common uniform tax may result in a higher welfare gain compared to taxing plastic bags alone, illustrating the importance of leakage in the studied context. In particular, incomplete regulation of the shopping bag markets can lead to increased environmental damage, in particular in terms of greenhouse gases emissions. Interestingly, the findings suggest that simultaneously regulating plastics and paper bags through a common uniform tax can be both environmentally and economically more efficient compared to a single tax on plastics, potentially leading to welfare improvements.

Nevertheless, the optimal choice between a uniform tax and only taxing plastic bags depends on factors such as the half-life of plastics and littering rates in the marine environment. This underlines the importance of considering a country's plastic waste management system when designing regulatory policies. For example, in regions characterized by relatively higher littering rates such as East Asia and Africa (Meijer et al., 2021), the imposition of taxes solely on plastic bags may be a viable strategy.

Furthermore, the implementation of environmental taxation requires careful deliberation, as its effectiveness depends on a multitude of factors. As discussed in a comprehensive review by Tan et al. (2022), key factors for the success of such taxes include legislation and institutional frameworks, education and public awareness initiatives, as well as administration and management capabilities. Frequently, these critical components exhibit comparatively lesser robustness within developing nations, thus necessitating prudent evaluation before the adoption of such policy measures. Moreover, the results from the cost-benefit analysis regarding the choice of environmental taxation strategy remain robust despite the assumptions made about economic parameters. This contrasts with findings by Koley (2022), which demonstrate that policy recommendations regarding the management of another long-lived pollutant, arsenic, found in shallow groundwater in West Bengal, India, are sensitive to assumptions regarding the future price of arsenic-laden bricks, which serve as a pollutant sink.

While this study enhances the understanding of regulatory strategies for mitigating marine pollution while simultaneously considering climate change, it is essential to acknowledge some limitations. First, the primary focus on taxation as a preventive measure to address marine pollution should be contextualized within a broader landscape of comprehensive mitigation strategies adopted by many nations, encompassing waste reduction, improved waste management practices, and environmental recovery initiatives (Borrelle et al., 2020). Future research should explore the synergistic interactions between these diverse mitigation strategies and policy instruments, aiming to ascertain their combined cost-effectiveness and overall impact.

Second, the paucity of data regarding price elasticities of demand for plastic and paper bags entails challenges in accurately estimating demand functions. Future research should prioritize the estimation of up-to-date demand elasticities, utilizing the most recent and relevant data sources to enhance the precision and robustness of welfare analyses. Also, we do not study the adjustment path towards a new equilibrium. The short-run impacts might differ from the effects in the longer term: results in Dikgang et al. (2012) suggest that the effect of taxes diminishes over time as consumers become accustomed to the levy and due to the low relative price of bags in terms of consumer incomes, while results in Mensah (2021) pointing in the opposite direction, suggesting larger adoption possibilities in the longer term. Finally, due to the limited extent of research dedicated to quantifying environmental damage caused by plastics in marine ecosystems, this study necessitated the formulation of simplifying assumptions. Future research should conduct in-depth investigations into the specific environmental damage of plastics.

6. Conclusions

This study has analyzed first- and second-best regulations aimed at mitigating environmental externalities, specifically addressing marine pollution and greenhouse gas emissions, associated with shopping bags made of both plastic and paper materials. Considering the prevailing influence of media coverage that often portrays plastic bags as environmentally detrimental, this research substantiates the higher environmental costs linked to plastics, providing a rational basis for the widespread practice of imposing taxes on plastic bags in many countries. However, the findings point to the potentially higher benefits from a common uniform tax covering both plastic and paper bags, as compared to a tax solely targeting plastics. It is crucial to recognize that the specific outcomes are contingent on variables such as plastic degradation rates and littering rates. It is recommended to interpret the numerical results of this study with caution, emphasizing the importance of focusing on the broader regulatory framework for plastic and paper bags. This underscores the need for a nuanced and context-specific approach to designing regulations.

CRediT authorship contribution statement

Tenaw G. Abate: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Katarina Elofsson:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix I. Plastic carrier bag regulation in the EU

Table A1
Tax on plastic carrier bags in EU countries.

Country	Year of introduction	Remarks
Czech Republic	January 1, 2018	Plastic carrier bags with a thickness of less than 15 μm are exempt.
Denmark	1993	A levy on all carrier bags with a handle and a volume of at least 5 L. The Danish government has implemented a ban on the distribution of thin, lightweight plastic carrier bags with low rates of reuse in various retail settings. Additionally, the government has instituted a ban on the complimentary provision of carrier bags, irrespective of their material composition.
Estonia	January 1, 2019	
Finland	October 31, 2016	
Germany	July 1, 2016	On July 1, 2016, a voluntary agreement was established between the German Federal Environment Ministry and the German Trade Association (HDE). This agreement introduced a fee structure for carrier bags, whereby bags with a capacity ranging from five to 50 cents per bag would incur a fee, while larger and thicker bags would be subject to a fee of one euro.
Greece	January 1, 2018	Starting from January 1, 2018, a fee of 0.04€ per bag was implemented. Subsequently, as of July 1, 2018, the fee was increased to 0.08€ per bag.
Ireland	2002	
Italy	August 1, 2017	
Lithuania	December 31, 2018	Lightweight plastic bags, 15 to 50 μm thick.
Luxembourg	December 31, 2018	
Netherlands	January 1, 2016	A mandatory fee of 0.25 euros per plastic bag.
Poland	January 1, 2018	Up to 1PLN (0,24 euro) per bag.
Romania	January 1, 2009	Eco-tax of 0.1 Lei (0.02 euro) per bag.
Slovakia	January 1, 2018	
Spain	January 1, 2018	A minimum price ranges from 5 to 30 cents depending on the thickness and material of the bags.
Sweden	March 1, 2020	A tax of 3 SEK (0.3 euro) per bag is levied on single-use plastic carrier bags. However, for small plastic bags with a thickness of less than 15 μm and a volume below 7 L, the tax is set at 0.30 SEK (0.03 euro) per bag.
United Kingdom	October 5, 2015	In England, a compulsory fee has been implemented for plastic carrier bags, which applies to businesses employing 250 or more individuals. Conversely, there are no equivalent obligations for paper carrier bags. Wales was the first to introduce a mandatory fee in 2011, which encompassed both plastic and paper carrier bags. Northern Ireland subsequently adopted this policy in 2013, followed by Scotland in 2014.

Sources: https://www.thepaperbag.org/for-compliance-with-the-law/regulations-in-eu

Appendix II. Consumption of Lightweight Plastic Carrier Bags in the EU

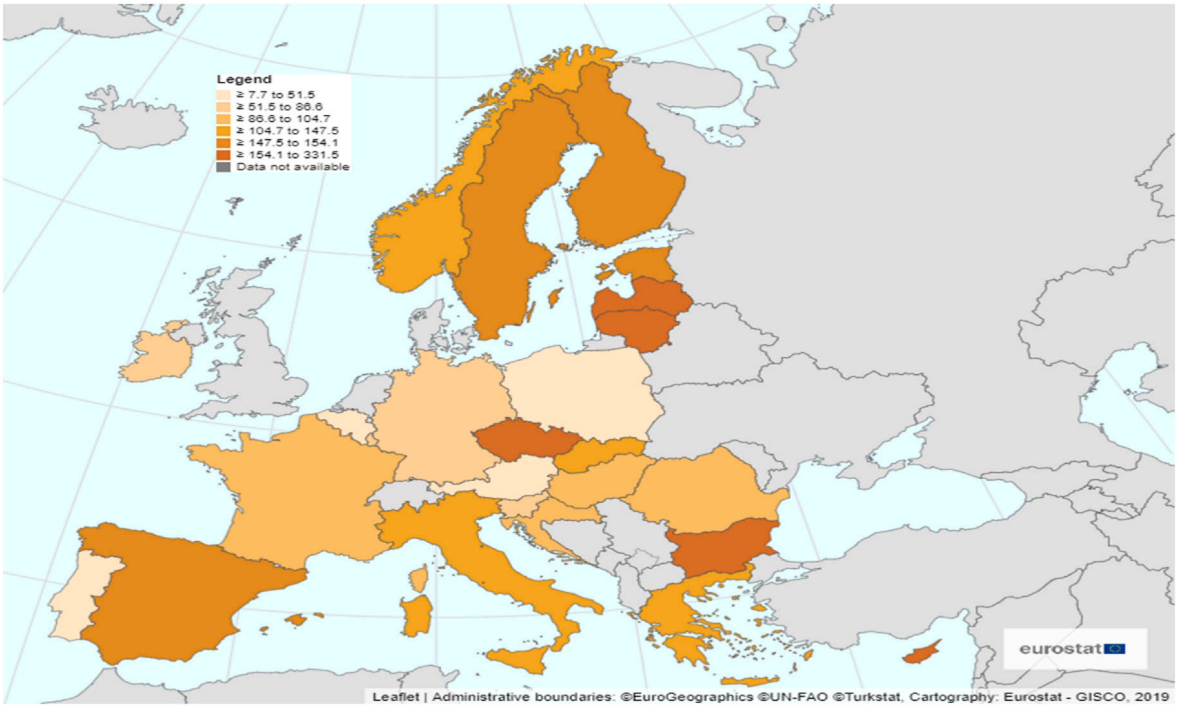

Fig. A1. Consumption of lightweight plastic carrier bags (less than 50 μm) in the EU in 2019.

Appendix III. Interpretation of the Common Uniform Tax

$$\tau = \frac{E'_x\left(B''_{xy} - B''_{yy}\right)}{\left(B''_{xy} - B''_{yy}\right) - \left(B''_{xx} - B''_{yx}\right)} - \frac{E'_y\left(B''_{xx} - B''_{yx}\right)}{\left(B''_{xy} - B''_{yy}\right) - \left(B''_{xx} - B''_{yx}\right)}. \tag{13}$$

The optimal common fee is a weighted average of the individual optimal Pigouvian taxes (t_i) that would be charged under the first-best regulation. The weight attached to the individual optimal Pigouvian tax for each good depends on the slopes of the demand curves of both products (B''_{xx} and B''_{yy}), and the strength of the substitution effects (B''_{xy} and B''_{yx}). The weight put on the marginal damage of each good is inversely related to the slope of the demand curve for the same good (This is shown below by taking the first order derivate of equation (13) with respect to the slope of the demand curve for plastic bags (B''_{xx}) and paper bags (B''_{yy}) which confirms this intuition). The intuitive explanation is that a flatter demand curve for a good implies a larger distortion in consumption in response to a given deviation from the Pigouvian tax. This then leads to a higher weight being placed on the environmental damage from that good, because deviations from the first-best tax choice are costly in welfare terms. The overall effects of the slope of the demand curves on the common uniform tax further depend on the relative magnitude of the marginal environmental damage costs of the two products. For example, if $E'_x > E'_y$, an increase in B''_{xx} will lead to a lower τ and vice versa. The impact of the strength of the substitution effect (B''_{xy} or B''_{yx} as they are symmetrical) is not straightforward as the sign of the first-order derivative of equation (13) (as shown below) with respect to B''_{xy} or B''_{yx} depends on the slope of the respective demand curves. If the slope of the demand curve for paper bags is steeper than for plastic bags ($B''_{yy} > B''_{xx}$), a stronger substitution effect will lead to a higher weight for plastic bags and vice versa.

The derivatives of equation (13) with respect to different parameters

$$\frac{\partial \tau}{\partial B''_{xx}} = \frac{\left(E'_x - E'_y\right)\left(B''_{xy} - B''_{yy}\right)}{\left(B''_{xy} - B''_{yy} - B''_{xx} + B''_{yx}\right)^2}$$

$$\frac{\partial \tau}{\partial B''_{yy}} = \frac{\left(E'_x - E'_y\right)\left(B''_{xx} - B''_{yx}\right)}{\left(B''_{xy} - B''_{yy} - B''_{xx} + B''_{yx}\right)^2}$$

$$\frac{\partial \tau}{\partial B''_{xy}} = \frac{\left(E'_x - E'_y\right)\left(B''_{yx} - B''_{xx}\right)}{\left(B''_{xy} - B''_{yy} - B''_{xx} + B''_{yx}\right)^2}$$

$$\frac{\partial\tau}{\partial B''_{yx}}=\frac{\left(E'_x-E'_y\right)\left(B''_{yy}-B''_{xy}\right)}{\left(B''_{xy}-B''_{yy}-B''_{xx}+B''_{yx}\right)^2}$$

Appendix IV. Converting the parametric direct demand functions into indirect demand functions

To straightforwardly calculate the second-best taxes, the direct demand functions are converted into indirect ones.

$$P_x=\frac{a_0b_1-a_2b_0}{a_2b_2-a_1b_1}-\frac{b_1}{a_2b_2-a_1b_1}Q_x+\frac{a_2}{a_2b_2-a_1b_1}Q_y$$

and

$$P_y=\frac{a_1b_0-a_0b_2}{a_2b_2-a_1b_1}-\frac{a_1}{a_2b_2-a_1b_1}Q_y+\frac{b_2}{a_2b_2-a_1b_1}Q_x$$

The independent tax only on plastic bags is given by equation (5) and plugging in the parametric values and rewriting would yield:

$$\tau_x=E'_x-E'_y\frac{\frac{b_2}{a_1b_1-a_2b_2}}{\frac{a_1}{a_1b_1-a_2b_2}}=E'_x-E'_y\frac{b_2}{a_1}\ .$$

On the other hand, the common uniform tax rate on both plastic and paper bags is given by equation (13), and inserting the parametric values and rewriting would provide:

$$\tau=\frac{E'_x\left(B''_{xy}-B''_{yy}\right)}{\left(B''_{xy}-B''_{yy}\right)-\left(B''_{xx}-B''_{yx}\right)}-\frac{E'_y\left(B''_{xx}-B''_{yx}\right)}{\left(B''_{xy}-B''_{yy}\right)-\left(B''_{xx}-B''_{yx}\right)}=E'_x\frac{(a_2-a_1)}{(a_2-a_1)-(b_1-b_2)}-E'_y\frac{(b_1-b_2)}{(a_2-a_1)-(b_1-b_2)}\ .$$

Appendix V. Calculation of welfare change

The welfare effect of the different types of taxes is calculated with the assumption that income effects are negligible.

1. The welfare effect of the three taxes in the plastic bag market

fig. A2 illustrates that all three tax types, Pigouvian tax (PT), Independent tax (IT), and Common tax (CT), reduce the consumption of plastic bags compared to the initial quantity (Q_x^0). The analysis of consumer surplus change is based on the original price of paper bags, as suggested by Araar and Verme (2019), motivated by price path dependence between the two markets otherwise calculating welfare changes would be ambiguous. As a result, the price increases resulting from PT, IT, and CT lead to a corresponding reduction in consumer surplus, represented by the triangular areas Δadg, Δ bdf, and Δcde respectively.

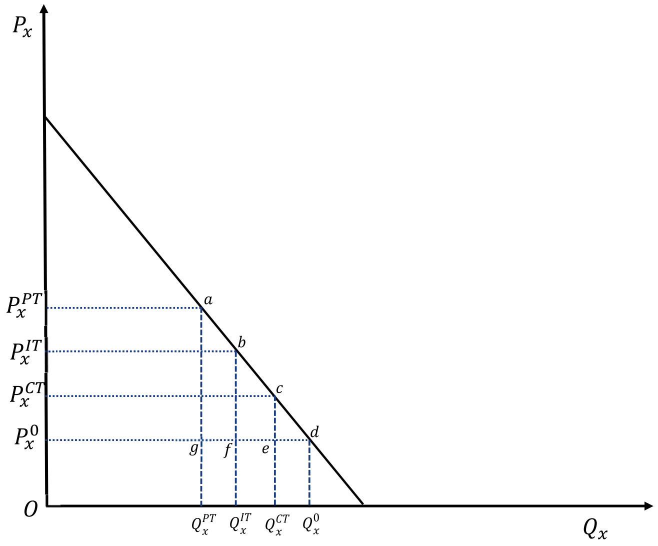

Fig. A2. The effect of the three taxes on plastic bag demand.

2. The welfare effect of the three taxes in the paper bag market

The implementation of the Pigouvian tax (PT) and Common tax (CT) has a similar impact on the demand for paper bags, leading to a reduction in their consumption compared to a tax-free scenario, as illustrated in fig. A3. However, fig. A3 demonstrates that when only plastic bags are subjected to taxation, the demand curve for paper bags shifts upward. This shift increases the consumption of paper bags, transitioning from the initial quantity denoted as Q_y^0 to Q_y^{IT}, while maintaining the price at P_y^0. The corresponding welfare change is calculated using the original demand curve and based on the observation that the new quantity Q_y^{IT} would then require a reduction in the price, which would be reduced to P_y^{-1}. The price reduction is not a real reduction, but rather a hypothetical one that would be necessary to make the new quantity (Q_y^{IT}) feasible on the original demand curve. The welfare change is then represented by the triangular area ($\Delta c^{'} h^{'} g^{'}$). The net consumer surplus changes resulting from these three tax regimes are determined by summing the respective triangular areas delineated in fig. A2 and fig. A3.

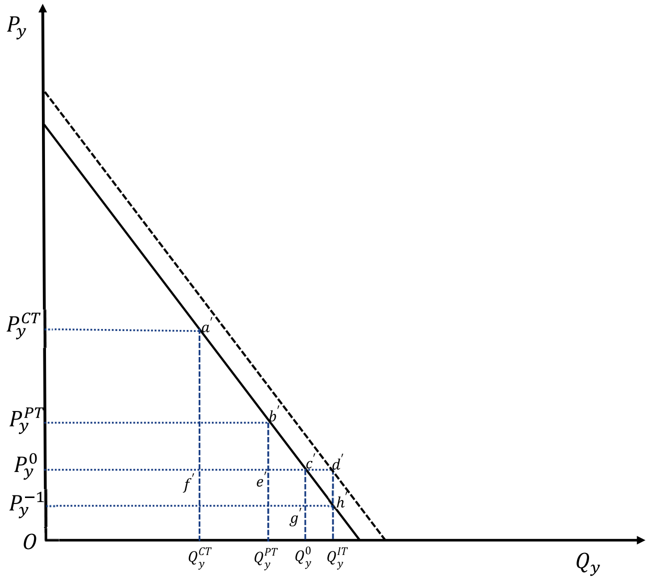

Fig. A3. The effect of the three taxes on paper bag demand.

References

Ahamed, A., Vallam, P., Iyer, N.S., Veksha, A., Bobacka, J., Lisak, G., 2021. Life cycle assessment of plastic grocery bags and their alternatives in cities with confined waste management structure: A Singapore case study. J. Clean. Prod. 278, 123956 https://doi.org/10.1016/j.jclepro.2020.123956.

Araar, A., Verme, P., 2019. Prices and welfare: an introduction to the Measurement of well-being when prices change. First ed. Cham. Springer International Publishing. http://link.springer.com/10.1007/978-3-030-17423-1.

BBC, 2019. Plastic or paper: Which bag is greener? URL: https://www.bbc.com/news/business-47027792. (Accessed 15 May 2023).

Beaumont, N.J., Aanesen, M., Austen, M.C., Börger, T., Clark, J.R., Cole, M., Hooper, T., Lindeque, P.K., Pascoe, C., Wyles, K.J., 2019. Global ecological, social and economic impacts of marine plastic. Mar. Pollut. Bull. 142, 189–195. https://doi.org/10.1016/j.marpolbul.2019.03.022.

BIO Intelligence Service, 2011. Assessment of impacts of options to reduce the use of single-use plastic carrier bags. Final Report prepared for the European commission-DG Environment.

Bisinella, V., Albizzati, P.F., Astrup, T.F., Damgaard, A. (Eds.), 2018. Life Cycle Assessment of Grocery Carrier Bags. Danish Environmental Protection Agency. Miljoeprojekter No. 1985. https://www2.mst.dk/Udgiv/publications/2018/02/978-87-93614-73-4.pdf.

Boesen, S., Bey, N., Niero, M., 2019. Environmental sustainability of liquid food packaging: is there a gap between Danish consumers' perception and learnings from life cycle assessment? J. Clean. Prod. 210, 1193–1206. https://doi.org/10.1016/j.jclepro.2018.11.055.

Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G.H., Hilleary, M.A., Eriksen, M., Possingham, H. P., Frond, H.D., Gerber, L.R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., Rochman, C.M., 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science. https://doi.org/10.1126/science.aba3656.

Brink, C., van Grinsven, H., Jacobsen, B.H., Rabl, A., Gren, I.-M., Holland, M., Klimont, Z., Hicks, K., Brouwer, R., Dickens, R., Willems, J., Termansen, M., Velthof, G., Alkemade, R., van Oorschot, M., Webb, J., 2011. Costs and benefits of nitrogen in the environment. In: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment. Cambridge University Press, pp. 513–540. https://doi.org/10.1017/CBO9780511976988.025.

Cabrera, J.M., Caffera, M., Cid, A., 2021. Modest and incomplete incentives may work: pricing plastic bags in Uruguay. J. Environ. Econ. Manag. 110, 102525.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M., Scott, S.L., Suh, S., 2020. Degradation rates of plastics in the environment. ACS Sustain. Chem. Eng. 8 (9), 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635.

Civancik-Uslu, D., Puig, R., Hauschild, M., Fullana-i-Palmer, P., 2019. Life cycle assessment of carrier bags and development of a littering indicator. Sci. Total Environ. 685, 621–630. https://doi.org/10.1016/j.scitotenv.2019.05.372.

Convery, F., McDonnell, S., Ferreira, S., 2007. The most popular tax in Europe? Lessons from the Irish plastic bags levy. Environ. Resour. Econ. 38 (1), 1–11. https://doi.org/10.1007/s10640-006-9059-2.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Global Environ. Change 26, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44 (9), 842–852. https://doi.org/10.1016/S0025-326X(02)00220-5.

Dikgang, J., Leiman, A., Visser, M., 2012. Elasticity of demand, price and time: Lessons from South Africa's plastic-bag levy. Appl. Econ. 44 (26), 3339–3342. https://doi.org/10.1080/00036846.2011.572859.

DR, 2021. Vi dropper plastikposen, men hvad er egentlig bedste alternativ? URL. https://www.dr.dk/nyheder/indland/vi-dropper-plastikposen-men-hvad-er-egentlig-bedste-alternativ. (Accessed 15 May 2023).

Edwards, C, Meyhoff Fry, J, 2011. Lifecycle assessment of supermarket carrier bags available in 2006. Environment Agency, Bristol. ISBN: 978-1-84911-226-0.

Fell, H., Maniloff, P., 2018. Leakage in regional environmental policy: the case of the regional greenhouse gas initiative. J. Environ. Econ. Manag. 87, 1–23. https://doi.org/10.1016/j.jeem.2017.10.007.

Forbes, 2020. Is Paper A More Sustainable Flexible Packaging Material Than Plastic? URL: https://www.forbes.com/sites/woodmackenzie/2020/08/24/is-paper-a-more-sustainable-flexible-packaging-material-than-plastic/. (Accessed 15 May 2023).

Ford, H.V., Jones, N.H., Davies, A.J., Godley, B.J., Jambeck, J.R., Napper, I.E., Suckling, C.C., Williams, G.J., Woodall, L.C., Koldewey, H.J., 2022. The fundamental links between climate change and marine plastic pollution. Sci. Total Environ. 806, 150392.

Fowlie, M.L., 2009. Incomplete environmental regulation, Imperfect competition, and emissions leakage. Am. Econ. J. Econ. Pol. 1 (2), 72–112. https://doi.org/10.1257/pol.1.2.72.

Fullerton, D., Karney, D.H., 2018. Multiple pollutants, co-benefits, and suboptimal environmental policies. J. Environ. Econ. Manag. 87, 52–71. https://doi.org/10.1016/j.jeem.2017.08.003.

Gibson, M., 2019. Regulation-induced pollution substitution. Rev. Econ. Stat. 101 (5), 827–840. https://doi.org/10.1162/rest_a_00797.

Gomez, I.D.L., Escobar, A.S., 2022. The dilemma of plastic bags and their substitutes: a review on LCA studies. Sustain. Prod. Consum. 30, 107–116. https://doi.org/10.1016/j.spc.2021.11.021.

Gourevitch, J.D., Koliba, C., Rizzo, D.M., Zia, A., Ricketts, T.H., 2021. Quantifying the social benefits and costs of reducing phosphorus pollution under climate change. J. Environ. Manag. 293, 112838 https://doi.org/10.1016/j.jenvman.2021.112838.

Greene, J., 2011. Life Cycle Assessment of Reusable and Single-use Plastic Bags in California. CSU Chico Research Foundation.

Hanley, N., Shogren, J.F., White, B., 2007. Environmental Economics: in Theory and Practice, second ed. Palgrave Macmillan.

He, G., Pan, Y., Park, A., Sawada, Y., Tan, E.S., 2023. Reducing single-use cutlery with green nudges: Evidence from China's food-delivery industry. Science 381 (6662), eadd9884. https://doi.org/10.1126/science.add9884.

Holland, S.P., 2012. Emissions taxes versus intensity standards: second-best environmental policies with incomplete regulation. J. Environ. Econ. Manag. 63 (3), 375–387. https://doi.org/10.1016/j.jeem.2011.12.002.

Homonoff, T.A., 2018. Can small incentives have large effects? The impact of taxes versus bonuses on disposable bag use. Am. Econ. J. Econ. Pol. 10 (4), 177–210. https://doi.org/10.1257/pol.20150261.

Homonoff, T., Kao, L.-S., Selman, J., Seybolt, C., 2021a. In: *Skipping The Bag: the Intended And Unintended Consequences Of Disposable Bag Regulation* (No. W28499. National Bureau of Economic Research, w28499. https://doi.org/10.3386/w28499.

Homonoff, T., Taylor, R.L.C., Kao, L.-S., Palmer, D., 2021b. Harnessing behavioral science to design disposable shopping bag regulations. Behavioral Science & Policy 7 (2), 51–61. https://doi.org/10.1177/237946152100700205.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771. https://doi.org/10.1126/science.1260352.

Khoo, H.H., Tan, R.B.H., 2010. Environmental impacts of conventional plastic and bio-based carrier bags: Part 2: end-of-life options. Int. J. Life Cycle Assess. 15 (4), 338–345. https://doi.org/10.1007/s11367-010-0163-8.

Kimmel, R.M., 2014. Life Cycle Assessment of Grocery Bags in Common Use in the United States. Clemson University Press, Clemson, USA. Available from: https://tigerprints.clemson.edu/cgi/viewcontent.cgi?article=1006&context=cudp_environment/.

Koley, S., 2022. Sustainability appraisal of arsenic mitigation policy innovations in West Bengal, India. Infrastruct. Asset Manag. 40, 1–21. https://doi.org/10.1680/JINAM.21.00021.

Lindh, H., Olsson, A., Williams, H., 2016. Consumer perceptions of food packaging: contributing to or counteracting environmentally sustainable development?: consumer perceptions of food packaging. Packag. Technol. Sci. 29 (1), 3–23. https://doi.org/10.1002/pts.2184.

Meijer, L.J.J., van Emmerik, T., van der Ent, R., Schmidt, C., Lebreton, L., 2021. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Sci. Adv. 7 (18), eaaz5803.

Mensah, A.C.E., 2021. Tax elasticity of demand for plastic: the cause of plastic pollution in Ghana. Journal of Environmental Economics and Policy 10 (1), 28–42. https://doi.org/10.1080/21606544.2020.1765882.

Moore, M.A., Boardman, A.E., Vining, A.R., 2013. More appropriate discounting: the rate of social time preference and the value of the social discount rate. J. Benefit-Cost Anal. 4 (1), 1–16. https://doi.org/10.1515/jbca-2012-0008.

Muthu, S.S., Li, Y., Hu, J.Y., Mok, P.Y., 2011. Carbon footprint of shopping (grocery) bags in China, Hong Kong and India. Atmos. Environ. 45 (2), 469–475. https://doi.org/10.1016/j.atmosenv.2010.09.054.

Muthu, S.S., Li, Y., Hu, J.Y., Mok, P.Y., Ding, X., 2012. Eco-impact of plastic and paper shopping bags. Journal of Engineered Fibers and Fabrics 7 (1), 155892501200700. https://doi.org/10.1177/155892501200700103.

NYT, 2019. Plastic bags, or paper? Here's What to Consider When You Hit the Grocery Store. URL:. https://www.nytimes.com/2019/03/29/climate/plastic-paper-shopping-bags.html. (Accessed 15 May 2023).

Rennert, K., Prest, B.C., Pizer, W.A., Newell, R.G., Anthoff, D., Kingdon, C., Rennels, L., Cooke, R., Raftery, A.E., Ševčíková, H., Errickson, F., 2021. The Social Cost of Carbon: Advances in Long-Term Probabilistic Projections of Population, GDP, Emissions, and Discount Rates.

Schnurr, R.E.J., Alboiu, V., Chaudhary, M., Corbett, R.A., Quanz, M.E., Sankar, K., Srain, H.S., Thavarajah, V., Xanthos, D., Walker, T.R., 2018. Reducing marine pollution from single-use plastics (SUPs): a review. Mar. Pollut. Bull. 137, 157–171. https://doi.org/10.1016/j.marpolbul.2018.10.001.

Small, K.A., Verhoef, E.T., 2007. The Economics of Urban Transportation. Routledge.

Sokolow, L., Meiffren-Swango, C., Engstrom, J., 2024. Plastic Bag Bans Work: well-designed single-use plastic bag bans reduce waste and litter. Environment America Research & Policy Center and U.S. PIRG Education Fund. Available from https://environmentamerica.org/center/resources/plastic-bag-bans-work/.

Stafford, R., Jones, P.J.S., 2019a. Viewpoint – ocean plastic pollution: a convenient but distracting truth? Mar. Pol. 103, 187–191. https://doi.org/10.1016/j.marpol.2019.02.003.

Stafford, R., Jones, P.J.S., 2019b. We should not separate out environmental issues, but the current approach to plastic pollution can be a distraction from meaningful action. A response to Avery-Gomm et al. Mar. Pol. 107, 103585 https://doi.org/10.1016/j.marpol.2019.103585.

Steenis, N.D., van Herpen, E., van der Lans, I.A., Ligthart, T.N., van Trijp, H.C.M., 2017. Consumer response to packaging design: the role of packaging materials and graphics in sustainability perceptions and product evaluations. J. Clean. Prod. 162, 286–298. https://doi.org/10.1016/j.jclepro.2017.06.036.

Tan, Z., Wu, Y., Gu, Y., Liu, T., Wang, W., Liu, X., 2022. An overview on implementation of environmental tax and related economic instruments in typical countries. J. Clean. Prod. 330, 129688 https://doi.org/10.1016/j.jclepro.2021.129688.

Taylor, R.L.C., 2019. Bag leakage: the effect of disposable carryout bag regulations on unregulated bags. J. Environ. Econ. Manag. 93, 254–271. https://doi.org/10.1016/j.jeem.2019.01.001.

Taylor, R., Villas-Boas, S.B., 2016. Bans vs. fees: disposable carryout bag policies and bag usage. Appl. Econ. Perspect. Policy 38 (2), 351–372.

Verhoef, E., Nijkamp, P., Rietveld, P., 1995. Second-best regulation of road transport externalities. J. Transport Econ. Pol. 29 (2), 147–167.

Verhoef, E., Nijkamp, P., Rietveld, P., 1996. Second-best congestion pricing: the case of an untolled alternative. J. Urban Econ. 40 (3), 279–302. https://doi.org/10.1006/juec.1996.0033.

Wagner, T.P., 2017. Reducing single-use plastic shopping bags in the USA. Waste Management 70, 3–12. https://doi.org/10.1016/j.wasman.2017.09.003.

Walker, T.R., Grant, J., Archambault, M.-C., 2006. Accumulation of marine debris on an intertidal beach in an urban park (halifax harbour, nova scotia). Water Quality Research Journal 41 (3), 256–262. https://doi.org/10.2166/wqrj.2006.029.

Walker, T.R., Reid, K., Arnould, J.P.Y., Croxall, J.P., 1997. Marine debris surveys at bird island, South Georgia 1990–1995. Mar. Pollut. Bull. 34 (1), 61–65. https://doi.org/10.1016/S0025-326X(96)00053-7.

Wang, P., Deng, X., Zhou, H., Yu, S., 2019. Estimates of the social cost of carbon: A review based on meta-analysis. Journal of Cleaner Production 209, 1494–1507.

Zhang, Y., Buongiorno, J., 1998. Paper or plastic? The United States' demand for paper and paperboard in packaging. Scand. J. For. Res. 13 (1–4), 54–65. https://doi.org/10.1080/02827589809382962.