Socio-Economic Planning Sciences 92 (2024) 101817

Contents lists available at ScienceDirect

Socio-Economic Planning Sciences

journal homepage: www.elsevier.com/locate/seps

Municipal strategies, fiscal incentives and co-production in urban waste management

Fabio Fiorillo *, Elvina Merkaj

Polytechnic University of Marche, Italy

ARTICLE INFO

Keywords:
Urban waste
Citizens and firms
Co-production
Tax incentives

ABSTRACT

We present a theoretical model examining household, firm, and municipal strategies in urban waste management. The model incorporates co-production by households and firms and introduces a private collector as a municipal competitor in waste management. Households can only dispose of recycled waste through the municipal system, while firms can choose between municipal waste management and selling recycled waste to the private collector. The model resolves a sequential game between the municipality and firms, with the municipality setting rules on recycling capital and tax incentives, while firms and households decide on their optimal waste disposal practices.

The aim is to explain the decision-making process of municipalities, the impact of tax incentives on firms' waste management choices, and the implications of citizens and firms involvement in co-production activities. Findings contribute to the development of sustainable waste management practices towards the achievement of sustainable goals.

1. Introduction

Municipal waste, often referred to as urban waste, is defined as "waste from households and waste from other sources, such as retail, administration, education, health services, accommodation and food services, and other services and activities, which is similar in nature and composition to waste from households" (Directive 2018/851/EU). It represents about 27% of the total waste generated within the EU. Waste management covers the handling of waste generated by individuals and businesses, involving collection, transportation, monitoring, disposal, and recycling. This process ensures that waste is managed safely from its origin until it is either recycled or properly disposed of, preventing harm to the environment and human health.

Waste management represents a core responsibility of local governments and holds a prominent position on the urban policy agenda due to its critical implications for the environment, public health, and public investments. It presents also one of the major challenges for EU institutions. Recent EU directives have established ambitious targets for municipal waste collection and recycling, necessitating substantial investments in infrastructure, technologies, capacities, and processes in the near future.

Effective waste management is a multifaceted challenge influenced by a complex interplay of policies, regulations, socio-cultural contexts, environmental conditions, economic factors, and available resources [3–6]. Numerous stakeholders are involved in waste management, each with unique interests and concerns. Local governments are responsible to manage urban waste and coordinate the complex interactions among processes and stakeholders, with the goal of safeguarding the environment and conserving resources. It involves the careful balancing of costs and revenues, adherence to EU regulations, public education, and strategic investments in infrastructure and technology to meet ambitious recycling objectives. They implement various measures/policies to reduce waste, increase recycling, and minimizing landfill to ensure an efficient management of waste (The Waste Framework Directive 2008/98/EC). Another stakeholder in waste management are private waste management companies that handle waste collection, transportation, and disposal services. They offer services that complement or, in some cases, compete with municipal or government-run waste management programs. These companies often operate independently of government waste management agencies, although they may also engage in public–private partnerships (PPPs) or compete for service contracts awarded by municipalities through a bidding

* Corresponding author.
E-mail addresses: f.fiorillo@univpm.it (F. Fiorillo), e.merkaj@univpm.it (E. Merkaj).

[1] The EU encourages the involvement of private operators in waste management but leaves the organization and division of responsibilities between the public and private waste management sectors to the discretion of member states. Private waste management companies in EU countries typically operate within the industrial and commercial sector and secure contracts for municipal waste management [1].

https://doi.org/10.1016/j.seps.2024.101817
Received 6 July 2023; Received in revised form 11 November 2023; Accepted 11 January 2024
Available online 12 January 2024

process.[1] Households generate waste and are concerned about timely and convenient waste collection services. They may have an interest in recycling programs and actively engage in co-production activities to reducing waste and minimize environmental impact [8,9]. Firms produce waste, and their interests may include cost-effective waste disposal and adherence to waste management regulations. Some businesses may also aim to improve sustainability and reduce waste generation [10,11]. Government agencies at various levels (local, regional, and national) are responsible for setting and enforcing waste management regulations. Their interest is to protect public health and the environment by ensuring compliance with waste laws (The Waste Framework Directive 2008/98/EC).

Theoretical research has shown that government measures, like penalties and incentives, significantly influence the willingness of various participants to engage in waste recycling efforts. Previous studies have explored various aspects of waste management, using partial equilibrium approach, focusing on specific waste types or individual stakeholder behaviors. Du et al. [11] use an evolutionary game theory model to analyze how construction firms and the public behave with regard to illegal dumping of construction waste. They find that well-structured penalties and incentives can effectively reduce illegal dumping and encourage household participation. However, their analysis solely considers construction waste and does not account for other operational factors of the actors. In contrast, Choe and Fraser [12] develop a model for household waste management policies that addresses waste reduction efforts by firms and households, as well as the issue of illegal waste disposal by households. They conclude that government policies should adapt to varying levels of household waste reduction efforts, sometimes requiring explicit monitoring of illegal waste disposal. Other studies have considered waste management as a generic concept but often treated municipal decisions as exogenous. Tan and Guo [13] models a manufacturer, retailer and consumer decision-making under the impact of 4 exogenous government policies (no policies, incentive promotion, strong regulation, joint policy). They find that the government's policy can improve product recycling quality and remanufacturing technology, and therefore influence the effectiveness of the trading market. Other studies explore the influence of municipal policies on consumer or firm behavior related to recycling or co-production [9,14], without exploring the intricate interactions among all stakeholders.

Our research bridges this gap by taking a comprehensive approach, considering the entire waste management ecosystem and the interdependent decision-making strategies of households, firms, and municipalities. This novel perspective allows us to evaluate the strategies employed by municipalities in waste disposal and analyze the significant role played by tax incentives and co-production in achieving sustainable solutions for all actors.

An additional aspect of the model is the inclusion of a private waste management entity, which is a competitor of the municipal waste collection services, concerning the disposal of waste generated by firms. Citizens must decide how much time to allocate to recycling versus leisure and work to maximize their utility, while firms choose between municipal waste management and selling their recyclables to private collectors based on profit optimization. Municipalities play a pivotal role in managing waste by deciding on capital allocation and tax incentives to influence firms' choices while ensuring cost and target constraints are met. Co-production of citizens and firms is a critical aspect, involving various activities aimed at reducing waste, minimizing environmental impact, and conserving resources.

By solving a sequential game with three players, we can examine how changes in citizens' and firms' behavior regarding recycling efforts and their cost–benefit considerations influence municipalities' optimal solutions. We assess the municipality's behavior concerning the inclusion or exclusion of firms from the municipal waste system and discuss the redistributive implications of this behavior. We analyze the strategies employed by municipalities in waste disposal management and the roles played by tax incentives and co-production in achieving sustainable optimal solutions.

This research enhances the understanding of optimal strategies for municipalities in waste management systems. The insights derived from this theoretical model can provide guidance to policymakers and stakeholders in formulating effective fiscal strategies for waste management that harmonize economic, environmental, and social objectives.

2. Literature review

2.1. The role of the municipality in urban waste management in EU countries

In European Union (EU) countries members, local governments are responsible for waste management with the objective of safeguarding the environment and conserving valuable resources. This multifaceted role encompasses various critical functions, including waste collection, recycling program, and eco-friendly disposal practices. Through their efforts, municipalities contribute significantly to the well-being of their communities and the preservation of our planet's ecological balance. (Waste Framework Directive 2008/98/EC).

Municipalities are obligated to align their waste management practices with EU directives and regulations.[2] They are bound to achieve specific recycling targets. Waste policies and targets established by the EU consist of fundamental standards for the management of specific waste categories. In 2015, the European Commission proposed new targets for municipal waste of 60 percent recycling and preparing for reuse by 2025 and 65 percent by 2030 [19].

The design of waste management programs, tailored to meet EU recycling rate objectives, exhibits variation among countries, highlighting the decentralized structure of waste management in Europe. According to the European Parliament [20] in 2021, nearly half of all municipal waste in the EU was recycled or composted. Countries such as Germany, Bulgaria, Austria, and Slovenia have already met or exceeded the 60 percent recycling target. However, Portugal, Romania, Malta, and Greece are currently lagging in terms of performance in this regard.

Local governments use a variety of policy instruments to prevent waste generation and encourage recycling and material reuse. According the European Environmental Strategy, the main policies used by EU Countries are landfill tax, pay-as-you throw taxation or other tax incentives, incineration tax, landfill ban on organic waste or non-pretreated waste and Mandatory Separate collection of bio-waste fractions [19]. Studies emphasize the positive impact of policies like taxation and unit pricing systems on waste reduction, though the outcomes vary across countries. For instance, in Sweden, a tax of approximately 0.2 USD/kg resulted in a 35 percent reduction in waste [21]. Bueno and Valente [22] highlighted the success of the unit pricing system in Trento, Italy, leading to a substantial 38 percent reduction in unsorted waste. In the canton of Vaud in Switzerland, the introduction of a tax on unsorted

[2] The EU has progressively enriched the waste management legislation in the aim to accelerate the transition towards a circular economy. There are five directives that set the targets for municipal waste collection and management: (i) (The Landfill Directive 1999/31/EC), which sets out strict operational requirements for landfill sites limiting the municipal waste that can be landfilled from 2035 to 10%. (ii) (Waste Framework Directive 2008/98/EC) lays down waste management principles, defines the waste hierarchy emphasizing the importance of municipal waste management and sets some ambitious target for municipal waste recycling. (iii) The Single-Use Plastics Directive 2019/904/EU (amended in 2018) sets separate collection targets for plastic waste. (iv) The Packaging and Packaging Waste Directive 94/62/EC (amended in 2018) focuses on the management of packaging waste. (v) In 2020 the EU released the new Circular Economy Package [18] which seeks to accelerate the transition towards a circular economy containing targets on sustainable products, circular textile and new regulation regarding construction waste.

waste, ranging from 0.24 to 1.95 CHF in 2013, increased the price of a 35-liter bag from 0.24 to 1.95 CHF, resulting in a roughly one-fourth decrease in yearly unsorted household waste per inhabitant [23]. These studies underscore the importance of complementing such policies with accessible recycling facilities to further enhance their effectiveness in waste management.

Municipalities are responsible also for educating and raising awareness among citizens and businesses about responsible waste management, recycling practices, and adherence to local waste regulations (The Waste Framework Directive 2008/98/EC). Educational initiatives and awareness campaigns play a significant role in achieving these objectives [24,25] leading to long term behavioral-changes [26].

Waste management carries various costs for municipalities, including those associated with waste collection, transportation, and recycling. These costs include expenses related to labor, fuel, maintenance of waste collection vehicles and organizational cost [27]. Municipalities also invest in recycling facilities to enhance the effectiveness of waste management [28] and to comply with fast changing EU and national waste management regulations. Expenses arise from conducting public awareness campaigns, educating residents about proper waste disposal, and promoting recycling and waste reduction [29].

Municipalities often charge residents and businesses for waste collection services. The fee structure can vary, including flat rates, volume-based charges, or "pay-as-you-throw" models. While specific fee structures are not outlined in EU directives, the principles of cost recovery and incentives are encouraged in The Waste Framework Directive 2008/98/EC. The specific fee structure can vary by region or municipality within a country. For example, different region in the same country may use various fee structure, including flat rates and pay-as-you-throw model as in UK, Germany and Italy among others. Some municipalities generate revenue from other sources, such as the sale of recyclable materials, energy production from waste-to-energy facilities, government subsidies, fines for non-compliance, and grants to support waste management initiatives.

Balancing costs and revenues is essential for municipalities to maintaining an economically sustainable and environmentally responsible waste management system. Achieving financial equilibrium in waste management allows municipalities to provide consistent and high-quality services, meet regulatory requirements, invest in environmentally responsible practices, and reduce the financial burden on their constituents. The Waste Framework Directive 2008/98/EC promotes cost-effective waste management and resource efficiency.

2.2. *Co-production in waste recycling*

Co-production, defined as the "involvement of citizens, clients, consumers, volunteers and/or community organizations in producing public service" [30], has gained significant attention in recent years. The literature suggests that public services can be provided more efficiently by adopting a co-producing approach involving service recipients [31]. Co-production can have various influences on public services, such as enhancing citizens' involvement, facilitating more targeted and responsive services [32], and improving the efficiency and effectiveness of service delivery [33].

In the context of waste management, co-production can involve various activities such as sorting and separating recyclable materials, participating in recycling programs, and engaging in waste reduction practices. Co-production can influence the cost and efficiency of waste management. If citizens are actively involved in waste management activities, it can lead to cost savings for the entire society. For example, if citizens sort waste properly, it can reduce the cost of waste treatment and disposal. Overall, the benefits of co-production in waste management can include a reduction in the overall volume of waste that needs to be handled by municipal waste management systems, a decrease in environmental pollution, conservation of resources, and potential economic benefits through the recovery of valuable materials from waste refer to (see Landi and Russo [34], Alonso et al. [35]).

Co-production in waste recycling can be seen as a common good due to its potential benefits and value to society as a whole. It is a shared resource or activity that benefits everyone, regardless of their individual contributions. The collective action of firms and households in co-producing waste management services contributes to the well-being and sustainability of the community, making it a common good.

The literature highlights the potential benefits of co-production in public services and its relevance to waste management. It emphasizes the role of citizen participation in waste reduction, sorting behaviors, and the importance of creating convenient waste management practices through tax policies [36]. Di Liddo and Vinella [9] demonstrates that citizen engagement in waste management could expand the production possibility frontier if the municipality implement tax policies that make sorting more convenient relative to work. Wang et al. [37] describe a game that focuses on government strategies to encourage cooperation between consumers and waste collectors. Their findings suggest that appropriate incentives and penalties can make collectors and recyclers to engage more actively in recycling and reusing plastic waste. However, these policies are less powerful when citizens are less concerned about environmental preservation and particularly when the associated costs are high [38]. This implies that participation in co-production is influenced not only by public policies but also by various economic, environmental, and social factors. Cohen et al. [14] reached a similar conclusion while modeling the voluntary participation of citizens in recycling within the framework of specific government policy schemes. Their research underscores that effective waste management necessitates trust and cooperation between residents and the municipality. Czajkowski et al. [39] find that factors like social pressure, moral motivation and effort exert an impact on pro-environmental behaviors. These theories find evidence in various countries, including France [36], Serbia [39], and across the entire European Union [40].

In our model, we consider the effort invested in co-production activities, which include sorting and recycling, by both households and firms. We use two measures to assess household co-production. The first measure reflects their preference for civicness, which is determined by the importance they attach to the cleanliness of the city. The second, considers recycling productivity, evaluated based on the quality of the recycled waste they generate. Conversely, the extent of firms' involvement in recycling is assessed by the productivity of recycled waste. Firms that are more productive allocate greater effort to co-production, resulting in a higher quality of recycled waste. We contribute to the co-production literature by assessing its impact on the optimal choices made by households, firms, and municipalities in their interconnected interactions. Our findings underscore the critical role played by waste productivity, due to the co-production efforts of both citizens and firms, in determining the optimal waste management solutions for all the stakeholders. This underscores the intricate and interdependent nature of co-production behavior.

The implications of our research extend to policymakers, as we offer insights that can inform the development of effective policy initiatives. By recognizing the importance of co-production and its potential benefits, policymakers can design strategies and interventions that promote sustainability and facilitate the transition to a more circular economy.

3. The model

In our economic model, waste recycling is conceptualized as a co-produced service involving citizens and firms. There exist two possible collectors of waste: the municipal government and a private competitor company specializing in waste recycling and disposal. Different rules and considerations govern the recycling practices of citizens and firms.

Citizens. Households, who prioritize the cleanliness and tidiness of their city, choose to dedicate their time to earning a wage (w) for purchasing consumer goods (X). Simultaneously, they allocate a portion of their non-working time to actively participate in waste reduction and recycling activities, aligning with the principles of co-production theory. They exclusively dispose of their waste through the urban waste management system operated by the local government. Recycling plays a vital role in maintaining a clean environment, and citizens actively consider the cleanliness of their city when making decisions regarding their recycling efforts. This recognition of the intrinsic link between recycling and the overall cleanliness of the city underscores the importance of waste management co-production practices in ensuring environmental sustainability of the territory.

Firms. Firms operate within the municipality to produce consumption goods (Y) using the available local labor force. These consumption goods are then distributed to residents both within and outside the municipality. In our analysis, we assume that these consumer goods are perfectly identical, leading to a state of perfect competition among firms in the consumer goods market.[3] Moreover, firms are subject to more stringent waste production regulations. A portion of their waste is categorized as special and non-urban waste WST_S, necessitating specialized and costly treatment methods. This particular waste falls outside the purview of the municipal waste management system. The remaining portion of firms' waste can be disposed of through either the municipal waste management WSF_F, referred to as Non-Autonomous Recycling (NAR), or private recycling collector (WST_{AR}), defined as Autonomous recycling (AR). Unlike citizens, firms have the autonomy to choose between these two competing waste management service providers.

Municipality. The local government is responsible for organizing urban waste services to achieve recycling targets while simultaneously determining the tax burden on citizens and firms to cover the costs associated with municipal waste management.

The municipality has the ability to differentiate the fiscal treatment between the two regimes, leading to different tax rates ($\tau_F^{AR} \neq \tau_F^{NAR}$). Let us define the difference in fiscal treatment between the two waste management regimes as: $D = \tau_F^{AR} - \tau_F^{NAR}$,

The value of D reflects the fiscal policy implemented by the municipality to promote or discourage certain waste management practices. If $D > 0$, it indicates that there is a fiscal incentive for firms to opt for the municipal waste system (NAR). Conversely, if $D < 0$, firms receive by the municipality an incentive to dispose of waste through autonomous recycling (AR).

Waste. The total waste generated in the city can be defined as follows:

$$WST = WST_S + WST_{AR} + WST_{NAR} + WST_F + WST_Y, \tag{1a}$$

where WST_S, WST_{AR}, WST_{NAR} and WST_F represent waste produced by firms and considered as special waste (WST_S), waste recycled through private collectors (WST_{AR}), waste recycled through urban waste collector (WST_{NAR}), and waste that is accounted as not recycled urban waste (WST_F), respectively. WST_Y represents the waste embodied in the goods produced by firms and consumed by citizens, both within and outside the municipality. Consequently, the overall amount of waste produced in the city (WST) exceeds the waste resulting solely from consumption.[4] Note that the total waste to be disposed through municipality waste management is $WST - WST_Y + WST_X$, since a quote of consumption goods is exported out of the municipality and a quote is imported. If municipality is a net importer of goods $X - Y > 0$, it imports also waste $WST_X - WST_Y > 0$, the converse is true when municipality is a net exporter of goods. For simplicity we assume that each unit of consumption good consumed equal to a unit of waste, thus $X = WST_X$ and $Y = WST_Y$.

3.1. Timing of the sequential game

The problem under consideration can be conceptualized as a sequential game. Initially, the central government establishes the criteria for classifying waste as urban waste and determines the recycling targets for municipalities. These factors are treated as exogenous variables in our model.

Next, the municipality decides on the allocation of resources to be distributed among citizens and firms for recycling purposes. The primary objective of the municipality is to minimize the cost associated with waste collection services while meeting the recycling targets set by the government. Consequently, the municipality must carefully set the taxation levels imposed on both citizens and firms to cover the costs in order to achieve the optimal solution. Additionally, taxes determine fiscal incentives influencing the decision-making of firms.

In the subsequent step, citizens and firms make their respective decisions. Citizens are responsible for choosing their consumption levels, labor supply, and the effort they will dedicate to waste co-production and recycling as an alternative to work and leisure. Firms, on the other hand, decide the level of production and whether to allocate waste to the municipal waste collector or a private waste management entity.

To solve this game, we employ a backward induction approach. Initially, we determine the optimal choices made by firms and households. Subsequently, we establish the municipal instruments and examine the impact of government measures on the optimal behavior of the municipality.

4. Production side

The production side of each municipality involves multiple firms that are considered collectively. These firms employ one unit of labor to produce a unit of consumption goods (Y) and b units of waste (WST) which, if not properly managed, can reduce the city's cleanliness.

Firms generate waste, but they are not responsible of the one embodied in the consumption of citizens ($WST - WST_Y = (b-1)Y$). Here, bY represents the total production of waste, and Y corresponds to the waste generated by citizens within and outside the municipalities through their consumption.

The waste on which firms are responsible can be classified into special and normal waste:

$$(b-1)Y = WST_S + WST_{AR} + WST_{NAR} + WST_F. \tag{1b}$$

Special waste. Special waste (WST_S) refers to waste that requires special treatment and processes for proper disposal. Examples include hazardous chemicals, construction materials, and heavy waste. Special waste is expressed as $WST_S = sY$, where $s \leq b-1$ represents the percentage of special waste generated by firms during production. Special waste does not contribute to urban waste and is not subject to taxation. However, the special treatment required for this type of waste incurs a cost for the firms, denoted as $\chi WST_S = \chi sY$, where χ is the unit cost of special waste.

[3] The assumption of perfect competition, coupled with the mobility of goods across different regions and the immobility of the labor force, results in the wage rate (w) adjusting endogenously to maintain a zero-profit condition for businesses. This implies that, in the absence of income distribution considerations, our model is equivalent to a scenario where a fixed value for w is set, and all incomes, including profits, are distributed to the residents within the municipality.

[4] Further elaboration on this aspect will be provided in subsequent sections.

Urban waste. Urban waste, also referred to as normal waste can be managed through two different approaches: the municipal waste management and private waste management. When firms choose to dispose of their waste through the municipal waste collector, it is categorized as urban waste or non-autonomous recycling ($i = NAR$). On the other hand, if firms opt for private waste management collectors, it is considered autonomous recycling ($i = AR$), usually it not considered within waste recycled by municipality.

The recycling activity of firms depends on the production factors used. We define the aggregation of all production factors used for recycling activity as capital (K_i). More properly, capital includes all equipment used for collection of waste, such as bins, trucks, sorting bags for recycling, as well as the organizational measures required for recycling. In particular, we assume that the quantity of recycled waste produced by firms is $WST_i = (1+\alpha)K_i$. Where K_i is the quantity of production factors used in recycling.[5] $1+\alpha$ represents the marginal productivity in recycling of capital used by firms, or for shortness the recycling productivity of the firms.[6]

In the context of autonomous recycling, firms have the option to sell their recyclable materials (WST_{AR}) to private waste managers at a unit price of p_R. In this case, the decision on the amount of capital K_{AR} is made by firms. Hence, engaging in autonomous recycling activities incurs a cost for firms, represented by γK_{AR}. The quantity of recycled waste destined for private waste management providers is determined by the capital required for recycling and recycling productivity, given as $WST_{AR} = rY = (1+\alpha)K_{AR}$, where r denotes the rate at which firm dispose of their waste through AR. In the case of non autonomous recycling, the amount of capital K_{NAR} is provided by municipality, not by firm. In this case, the amount of recycled waste is $WST_{NAR} = (1+\alpha)K_{NAR}$.

Obviously, the amount of recycled waste cannot exceed the maximum amount of waste produced, leading to the constraint:

$$WST_i = (1+\alpha)K_i \leq (b-1-s)Y, \; i = AR, NAR. \tag{2}$$

4.1. Maximization problem of firms

This section focuses on the maximization problem faced by firms in the context of waste management. The assumptions made include the restriction that firms can only hire labor from within the municipality, the assumption of perfect substitution between consumption goods produced within the municipality and those produced elsewhere, coupled with free entry of firms, ensures perfect competitive market of consumption goods with zero-profit condition; it is clear that since workers are not mobile while goods are, the wages in each municipal could be different.

The objective is to determine the optimal choices of waste management and labor demand that maximize firm profits.

The joint production function of firms is expressed as follows:

$$Y = L; WST = bY = bL.$$

Here, $\frac{1}{b}$ represents the constant input of labor required to produce one unit of waste. Firms can hire labor (L) only within the municipality but have the flexibility to sell consumption goods both within and outside the municipality. The price of consumption goods (p_Y) is assumed to be given and equal in all municipalities, with $p_Y = 1$.

The firms' maximization problem can be formulated as follows:

$$\max_{r,L} \Pi = \max_{r,L} L + \left(p_R - \frac{\gamma}{1+\alpha}\right) rL + \\ - wL - \chi sL - (b-1-s)\tau_F L. \tag{3}$$

In the objective function (3), $L + p_R rL$ represents the revenues generated from production and selling waste to private waste management. wL denotes the cost of the production input, $\gamma K_{AR} = r\frac{\gamma}{1+\alpha}L$ represents the costs incurred in the case of autonomous recycling, χsL represents the cost of special waste, and $(b-1-s)\tau_F L$ is the tax that firms must pay for waste production.

To find the optimal solutions, we aim to determine the values of r and L that maximize the objective function. In this case, the objective function is linear with respect to r and L, indicating that the optimal solutions will be corner solutions.

Maximizing with respect to r allows us to determine the optimal level of waste disposal through autonomous recycling (r) in alternative to NAR. This decision depends on the relative profitability of the two options. If the price received for selling waste is greater than the cost of waste disposal through autonomous recycling ($p_R > \frac{\gamma}{1+\alpha}$), it is optimal for the firms to dispose all their waste through autonomous recycling, which corresponds to the maximum value of r (i.e., $r = b-1-s$). On the other hand, if p_R is lower than $\frac{\gamma}{1+\alpha}$, it is optimal for the firms to set r to its minimum value of 0.

Maximizing with respect to L allows us to determine the optimal level of employment for the firms that maximize revenues generated by production and waste disposal while considering the associated costs of labor and other inputs. Additionally, we impose a zero profit condition to allow free entry of firms and ensure that firms operate in a competitive environment, where the entire value added is allocated as wages. The wage rate adjusts accordingly to satisfy the zero profit condition[7]:

$$w = 1 - \chi s - (b-1-s)\tau_F \\ + \left(p_R - \frac{\gamma}{1+\alpha}\right) r. \tag{4a}$$

Here, $\left(p_R - \frac{\gamma}{1+\alpha}\right)$ represents the profit (or loss) per unit of waste obtained by selling normal waste to private waste management (in the case of autonomous recycling, AR). The zero profit condition ensures that the entire value added produced by firms is distributed to citizens as wages. It means that firms do not retain any profits for themselves, but instead allocate the entire value created by their activities to compensate their employees. By imposing the zero profit condition, the decision-making process focuses on maximizing the distribution of value added to citizens rather than accumulating profits for the firms. This approach is aligned with the idea that the profit generated by firms should directly benefit the local community. In this way, the zero profit condition emphasizes the role of firms in contributing to the local economy.

[5] We assume that the quantity of waste recycled by firms is independent of the labor force they employ for the production of consumption goods. Instead, it relies on additional factors, which we have define as "capital" for brevity. It is essential to note that the possibility of allocating both labor and capital to the production of consumption goods and recycled waste does not alter the core results of our model. We discuss this aspect in our concluding remarks.

[6] The assumption of constant returns to scale is justified by our definition of capital, which includes all the production factors used by firms. Furthermore, we consider that a unit of capital generates the same quantity of recycled waste, regardless of whether it is acquired by companies (AR) or provided by the municipality (NAR).

[7] If we do not consider free entry, we can achieve the same outcomes by assuming that all the value added, which comprises wages and profits generated by the firms, is distributed among the workers. In this scenario, the right-hand side of Eq. (4a) would be equal to $w+\Pi$, where Π represents the profits earned by the firms. However, when we take into account distributive aspects, profits need to be allocated to consumers distinct from the workers. We discuss briefly some redistribution extension of our model in the concluding remarks.

4.2. The choice of firms between municipal (NAR) or private waste management (AR) and fiscal incentives

In the context where all firms' profits are allocated to the citizens through wages, firms' objective becomes the selection of the waste management regime (AR or NAR) that maximizes the value added distributed as wages to the citizens. The value added represents the net economic gain or the contribution of the firms' activities to the local economy.[8]

When considering autonomous recycling, the value added produced, which takes into account various parameters such as the waste collection cost, the fiscal premium, and the quantity of waste disposed, is given by:

$$\begin{aligned} w^{AR} &= 1-\chi s-(b-1-s)\tau_F^{AR} \\ &+ \left(p_R-\frac{\gamma}{1+\alpha}\right)(b-1-s). \end{aligned} \tag{4b}$$

On the other hand, when waste is disposed to the municipal waste management system (NAR), the value added produced is:

$$w^{NAR} = 1-\chi s-(b-1-s)\tau_F^{NAR}. \tag{4c}$$

Firms will choose the disposal regime by comparing the value added of AR (w^{AR}) with the value added of NAR (w^{NAR}). This can be expressed as the difference between (4b) and (4c):

$$\begin{aligned} w^{AR}-w^{NAR} &= \left[\left(p_R-\frac{\gamma}{1+\alpha}\right)-(\tau_F^{AR}-\tau_F^{NAR})\right](b-1-s) \\ &= \left[\left(p_R-\frac{\gamma}{1+\alpha}\right)-D\right](b-1-s). \end{aligned} \tag{5}$$

If this difference is negative ($w^{AR}-w^{NAR}<0$), firms will prefer the NAR regime when $p_R-\frac{\gamma}{1+\alpha}<D$. In other words, if the fiscal premium offered by the municipality (D) is higher than the potential profit from the private waste collector ($p_R-\frac{\gamma}{1+\alpha}$), firms will choose the NAR regime. Conversely, if the difference in wages between AR and NAR regimes is positive ($w^{AR}-w^{NAR}>0$), firms will prefer the AR regime.[9]

The derivatives with respect to various parameters show how changes in those parameters affect the difference in value added between the two regimes providing additional insights into the firms' decision-making process.

Proposition 1. $\frac{d}{dp_R}\left(w^{AR}-w^{NAR}\right)\geq 0$, $\frac{d}{d\alpha}\left(w^{AR}-w^{NAR}\right)\geq 0$, $\frac{d}{d\chi}\left(w^{AR}-w^{NAR}\right)\leq 0$ *and* $\frac{d}{dD}\left(w^{AR}-w^{NAR}\right)\leq 0$.

Proof. Proof is straightforward. □

The derivatives demonstrate that a decrease in the revenue for recycling (p_R) or the firm recycling productivity (α), an increase in the recycling cost (γ), or an increase in the fiscal premium (D) would make firms more likely to choose the municipal waste collector. Conversely, a decrease in these variables favors autonomous recycling.

Proposition 2. *If* $s<b-1$, $\frac{d}{ds}\left(w^{AR}-w^{NAR}\right)\gtreqless 0$ *if* $w^{AR}-w^{NAR}\lesseqgtr 0$. *Moreover* $w^{NAR}=w^{AR}$ *if* $s=b-1$.

Proof. Proof in the appendix □

Proposition 3. $\frac{d}{db}\left(w^{AR}-w^{NAR}\right)\gtreqless 0$ *if* $w^{AR}-w^{NAR}\gtreqless 0$

Proof. Proof in the appendix □

Propositions 2 and 3 state that the amount of special waste (s) and the total waste production (b), exogenously imposed by the government, does not influence firms' decision in choosing the collector, but they does affect the economic advantage associated with that choice.

An increase in the amount of special waste (s) and a decrease in total waste production (b), diminishes the economic advantages of the preferred waste management regime compared to the alternative. This relationship arises because in both cases firms will need to dispose of a lower volume of urban waste through their chosen waste management regime (either AR or NAR). Conversely, the opposite holds. Moreover, when $s=b-1$, firms become indifferent between the two regimes, as they cannot dispose of waste through the municipal collector.

The government and municipality can shape the decision-making process of firms towards more sustainable waste management practices, promote waste recycling and create a favorable environment for a circular economy.

5. Households

In this section, we aim to investigate the behavior of households considering their preferences and waste taxation. In our model, we assume that each citizen possesses one unit of time that can dedicate to labor, leisure or recycling [8]. Citizens collectively "own" the cleanliness of the city and pay waste taxes.

The utility of each citizen, denoted as u^i, with $i=AR,\ NAR$, is positively influenced by their consumption (x^i), by the fraction of time dedicated to leisure ($1-l^i-h^i$), where (l^i) represents the fraction devoted to work, and by the level of recycling activity, where (h^i) represents the fraction devoted to recycling. Let $X^i = x^iN$, $L^i = l^iN$ and $H^i=h^iN$ denote the aggregate quantities of consumption, labor, and recycling time, respectively, where N represents the total population. The aggregate citizens' income gross of taxes is $M^i=w^iL^i$.

Following Di Liddo and Vinella (2020), we consider households as a whole, maximizing their aggregate utility function in two steps. In the first step, households decide how to allocate their time between labor (L) and consumption (X). Subsequently, they allocate the remaining time between leisure and recycling.

In the first step, the objective is to maximize the utility U^i with respect to consumption X and labor input L, subject to the budget constraint:

$$\begin{aligned} &\max_{X,L} U^i = \theta\ln X^i+(1-\theta)\ln(N-L^i) \\ &\text{s.t. } (1+\tau_C)X^i = M^i \end{aligned} \tag{6a}$$

The parameter θ captures the preference for consumption over other activities, while τ_C represents the waste taxation rate payed by citizens and M^i represents the citizens gross income in scenario i.[10] Taxation on citizens reduces consumption and, consequently, waste.

The solutions to this optimization problem are straightforward: $L^i=\theta N$, $N-L^i=(1-\theta)N$ and $X_i=\frac{w^i}{1+\tau_C}\theta N$.

Moving to the second step, citizens maximize their utility by determining the optimal level of recycling activity H. The objective is to maximize:

$$\begin{aligned} &\max_H \beta R_C^i+\ln[(1-\theta)N-H^i] \\ &s.t. R_C^i = K_C^i(1+H^i) \end{aligned} \tag{6b}$$

In this equation, β represents the preference for civicness, which reflects the willingness of citizens to participate in recycling and restoring the cleanliness of the city.[11]

[8] Details in the appendix.

[9] This is true since $b-1-s\geq 0$.

[10] It is important to remind that waste and consumption are jointly produced in a 1-to −1 relationship. Therefore, a tax on waste increases the relative price of consumption compared to leisure.

[11] In contrast to Di Liddo and Vinella [9], who model citizens' behavior using a quasi-linear utility function in the first stage and a Cobb–Douglas function in the second, our approach employs a Cobb–Douglas function for the first stage and a quasi-linear utility function for the second. This choice is driven by the properties of the Coob-Douglaus that permits internal solutions and of the quasi-linear utility function, which allows for a potential corner

Higher is β, higher is the engagement of citizens in co-production activities in waste management. R^i_C represents the quantity of waste recycled by citizens which is co-produced using K^i_C, the capital provided them by municipality, and the time of citizens. It is evident that the productivity of capital provided depends by citizens time used in recycling activity $(1 + H^i)$. N represents the total available time for citizens. The term $(1-\theta)N - H^i$ represents the remaining time that citizens allocate to leisure activities after considering their preference for consumption and the time devoted to work and recycling (considered in the first step). This formulation captures a plausible behavior of citizens, where their level of civicness and willingness to engage in recycling activities are not solely determined by the waste taxation they pay. Instead, it is influenced by the labor supply conditions.

The solution of (6b) is the optimal level of recycling activity given by:

$$H^i = (1-\theta)N - \frac{1}{\beta K^i_C}. \tag{7a}$$

Therefore, the time devoted to recycling by citizens is increasing with the capital provided them by municipality (K^i_C) and with their civicness (β), while decreases with consumption preferences (θ). Therefore the optimal quantity of waste recycled is determined by the equation:

$$R^i_C = K^i_C[(1-\theta)N + 1] - \frac{1}{\beta} \tag{7b}$$

where $(1-\theta)N + 1$ is the marginal productivity in recycling of the capital used by citizens, or for shortness the productivity of citizens in recycling.

Proposition 4. $\frac{dR^i_C}{dK_C} > 0$, $\frac{dR^i_C}{d\beta} > 0$ *and* $\frac{dR^i_C}{d\theta} < 0$

Proof. Proof is straightforward □

The model suggest that the quantity of waste recycled by citizens, denoted as R^i_C, increases with the capital destined by the municipality to citizens' recycling (K_C). This means that increasing the availability and accessibility of recycling infrastructure can encourage citizens to participate in recycling activities and contribute to the cleanliness of the city. Moreover, the preference for civicness (β) plays also a significant role in determining citizens' willingness to engage in recycling and co-production activities. As β increases, citizens are more likely to allocate their time and resources towards recycling and co-production, even in the presence of waste taxation or other factors that might discourage participation.

Conversely, the waste recycled decreases with the citizens' preference for consumption (θ),[12] highlighting the trade-off between consumption and waste generation. As θ increases, indicating a stronger preference for consumption, citizens allocate more of their time and resources towards consumption and less towards recycling activities. Therefore, a higher value of θ leads to a decrease in the quantity of waste recycled by citizens.

Overall, the model suggests that waste taxation can be an effective policy tool for reducing waste production and promoting recycling. By increasing the relative price of consumption compared to leisure, waste taxation can incentivize households to allocate more time and resources towards recycling activities. Additionally, as waste taxation reduces citizens' preference for consumption (θ), it can indirectly increase the quantity of recycled waste.

6. Municipality

The objective of the municipality is to minimize the cost of recycling under two constraints. The first constraint is that tax revenues should cover the costs of recycling. The second constraint is imposed by the government, which sets a recycling target for the municipality, as a percentage σ of recycled waste relative to the total waste generated. Thus we may write:

$$\sigma = \frac{R^i_C + R^i_F}{WST^i_X + R^i_F + WST^i_F}, \tag{8}$$

where we recall that $WST^i_X = X^i$ and $R^i_C = K_C(1 + h^i)$. Moreover, we can define R^i_F as the recycled waste collected by municipality from firms and WST^i_F is the non recycled waste collected by municipality from firms in scenario i. Recalling that $R^{AR}_F = 0$ since in this scenarios no waste is dispose throughout municipal waste management and $WST^{AR}_F = 0$ since in case of opting for autonomous recycling, all waste is recycled. On the contrary the quantity recycled through municipal waste management depends on capital provided and firm productivity $R^{NAR}_F = WST_{NAR} = K_{NAR}(1+\alpha) \le (b-1-s)\theta N$, hence $WST^{NAR}_F = (b-1-s)\theta N - R^{NAR}_F$. Recycling waste cannot be greater of the total normal waste of which firms are responsible (that is equal to $(b-1-s)\theta N$).

To achieve its objective, the municipality needs to make decisions regarding the allocation of capital to firms and citizens for recycling, taxes on waste for both citizens and firms, and incentives provided to firms. The municipality aims to minimize its cost function, which can be expressed as:

$$\min_{\tau_C, \tau^{NAR}_F, D, K_C, K_{NAR}} cK_C + cK_{NAR} = \min_{\tau_C, \tau^{NAR}_F, D, K, K_{NAR}, s} c\Phi \tag{9}$$

where c represents the average unit cost of capital for the municipality, K_C and K_{NAR} denote the capital for waste recycling provided to citizens and firms, respectively, Φ is the total capital provided by municipality.

6.1. Cost coverage constraint

The cost coverage constraint can be expressed in terms of capital to be provided. There are two scenarios to consider:

AR regime. In the scenario where firms choose the private collector (AR), the constraint is given by:

$$\Phi \le \overline{\Phi}^{AR} = \frac{\theta N}{c}\left[1 - \chi s + \left(p_R - \frac{\gamma}{1+\alpha}\right)(b-1-s)\right] - \frac{X^{AR}}{c} \tag{10a}$$

where $\overline{\Phi}^{AR}$ is the maximum capital that can be provided in the AR scenario in order to cover the costs.

NAR regime. In the scenario where firms dispose of their waste to the municipal waste manager (NAR), the constraint for the municipality is given by:

$$\Phi \le \overline{\Phi}^{NAR} = \frac{\theta N}{c}\left[1 - \chi s\right] - \frac{X^{NAR}}{c} \tag{10b}$$

Here, $\overline{\Phi}^{NAR}$ represents the maximum capital that can be provided in the NAR scenario. In both scenarios, the cost of providing capital to citizens is negatively influenced by the consumption level.[13]

solution where no consumption occurs, which may not be realistic. Indeed, the use of the Cobb–Douglas utility function ensures that an internal solution exists for both consumption and time allocation. In this case, the time allocated to work is represented as a share of the total available time, denoted by $\theta < 1$, which is a more reasonable outcome.

[12] It is worth noting that the net amount of waste produced, accounting for recycling, is given by: $WST_X - R_C = \left(\frac{w^j}{1+\tau_C} - K_C\right)\theta N + K_C(N+1) + \frac{1}{\beta}$. This expression represents the remaining waste after the recycling process has taken place.

[13] Passages in Appendix A.

6.2. The recycling target constraint

The second constraint imposed on the municipality is to achieve the recycling target set by the government, represented by the percentage σ of recycled waste in relation to the total waste generated (8).

The specific form of the constraint depends on the chosen scenario by the firms.

AR regime. If the firms choose the AR scenario, the target constraint in terms of capital can be expressed as follows[14]:

$$\Theta \geq \hat{\Theta}^{AR} = \frac{\sigma}{(1-\theta)N+1} X^{AR} + \frac{1}{[(1-\theta)N+1]\beta} \tag{11a}$$

This equation represents the minimum capital that should be allocated to achieve the recycling target. It depends mostly on variables such as the recycling rate (σ), the total waste generated by citizens (X^{AR}), the preference for consumption compared to leisure or recycling (θ), the preference for civicness (β), the proportion of special waste.

NAR regime. In case firms choose NAR scenario, the recycling target constraint is slightly more complex:

$$\begin{aligned}\Theta \geq \hat{\Theta}^{NAR} &= \frac{\sigma}{[(1-\theta)N+1]} X^{NAR} + (b-1-s)\frac{\theta N}{[(1-\theta)N+1]} \\ &+ \frac{(1-\theta)N-\alpha}{[(1-\theta)N+1]} K_{NAR} + \frac{1}{[(1-\theta)N+1]\beta} \\ &\text{with } (1+\alpha)K_{NAR} \leq (b-1-s)\theta N.\end{aligned} \tag{11b}$$

In this scenario, the recycling target constraint takes into account various factors, including the waste generated by citizens (X^{NAR}), the proportion of waste generated by citizens (θ), the proportion of firms' special waste (s), the productivity difference between firms and citizens (α), and the capital allocated to firms (K_{NAR}), the citizens' preference for civicness (β), among others.

To minimize costs, the municipality aims to allocate the minimum amount of capital required to satisfy the recycling target constraint. The decision regarding the allocation of capital to firms becomes crucial. Allocating capital to firms may be wasteful if they choose the AR regime, where the entire waste is collected by private collectors. Therefore, it may be optimal to allocate capital to firms only in the NAR scenario.

It is important to note that the decision-making process of the municipality depends on the slope of the target constraint in the NAR scenario. The slope, represented by $\left(\frac{d\hat{\Phi}^{NAR}}{dK_{NAR}} = \frac{(1-\theta)N-\alpha}{(1-\theta)N+1}\right)$, can be positive or negative depending on whether firms are less or more productive than citizens ($\alpha < (1-\theta)N$ or $\alpha \geq (1-\theta)N$). This influences the municipality's decision on capital allocation.

In this context, we further analyzing Eq. (11b) that describe the recycling target constraints for firms that are less productive or more productive than citizens.

NAR regime when firm are less productive than citizens. In this case, ($\alpha < (1-\theta)N$), we have:

$$\begin{aligned}\hat{\Phi}^{NAR} &= \frac{\sigma}{[(1-\theta)N+1]} X^{NAR} + \frac{(b-1-s)\theta N}{[(1-\theta)N+1]} \\ &+ \frac{1}{[(1-\theta)N+1]\beta};\end{aligned} \tag{11c}$$

NAR regime when firm are more productive than citizens. In a context with firms more productive than citizens: $\alpha \geq (1-\theta)N$ the target constraint is expressed:

$$\begin{aligned}\hat{\Phi}^{NAR} &= \frac{\sigma}{[(1-\theta)N+1]} X^{NAR} + \frac{(b-1-s)\theta N}{[(1-\theta)N+1]}\frac{(1-\theta)N}{1+\alpha} \\ &+ \frac{1}{[(1-\theta)N+1]\beta}.\end{aligned} \tag{11d}$$

for the optimal solution of municipality, if firms are less productive than citizens, the capital allocation to firms (K_{NAR}) does not play a significant role in the recycling target constraint therefore it is set to zero. The focus is mainly on factors that depend on citizens like waste generation (X^{NAR}), the preference for consumption (θ), preference for civicness (β), and other exogenous factors set by the government like the target of recycling and the definition of urban waste. In the case when firms are more productive in waste recycling than citizens, the capital allocation to firms (K_{NAR}) becomes a more crucial factor in the recycling target constraint. Moreover, the recycling target depends not only on, same as before, factors characteristic to citizens like waste generation (X^{NAR}) and the proportion of waste generated by citizens (θ) or preference for civicness (β), but also on the productivity difference between firms and citizens (α).

These additional results highlight the importance of the productivity comparison between firms and citizens in the decision-making process of the municipality. The municipality needs to carefully consider the productivity levels of firms and citizens when determining the capital allocation strategy to achieve the recycling target set by the government. The optimal allocation of capital depends on whether firms are less productive or more productive than citizens, as reflected in the recycling target constraints.

6.2.1. Graphical representation of the second constrain

The graphical representation in Fig. 1 provides an intuitive understanding of the second constraint and its implications for the municipality's decision-making process regarding the allocation of capital for recycling.[15]

The figure consists of two graphs, each representing a different productivity comparison between firms and citizens in recycling. The x-axis represents the capital allocation to firms (K_{NAR}), while the y-axis represents the total recycling capital (Φ).

The left side presents the case when firms are less productive than citizens regarding recycling. Whereas the right graph considers the case of firms more productive than citizens. The dashed lines represent the cost that needs to be minimized (9), which decreases with an increase in capital allocation (K). The solid line represents the recycling target constraint when firms choose municipal collectors (11b). The constraint is a straight line that starts from point A (where $K_{NAR} = 0$) and intersects the cost curves. At point E, the municipality provides firms with the amount of capital ($K_{NAR} = (b-1-s)$) required to recycle all the waste they produce. This point corresponds to the intersection of the cost curve and the recycling target constraint for municipal collectors.

The dotted line represents the recycling target constraint when firms choose private collectors. The constraint is parallel to dashed lines but shifted upwards. At point E, the municipality provides firms with the optimal amount of capital (K_{NAR}) required to recycle all the waste they produce.

If firms are less productive in recycling than citizens $(1-\theta)N < \alpha$ ((11c), graph in the left), the solid line is increasing, hence, the optimal capital allocation for firms in this case is zero (point A). The municipality does not allocate any capital to firms, and the recycling target is achieved solely through citizen participation and municipal efforts.

If firms are more productive ((11d), graph in the right), the solid line representing the recycling target constraint is decreasing. Then, point E represents the optimal allocation of capital by the municipality, ensuring that firms can achieve the recycling target efficiently. At this point, firms receive the necessary capital ($K_{NAR} = \frac{b-1-s}{1+\alpha}\theta N$) to recycle all the waste they produce.

This graphical representation highlights the importance of the productivity comparison between firms and citizens in determining the optimal allocation of capital for recycling. It visually demonstrates how the recycling target constraint and the choice between municipal and private collectors vary based on the relative productivity levels.

[14] See the Appendix for more details.

[15] The figure considers X^i as given.

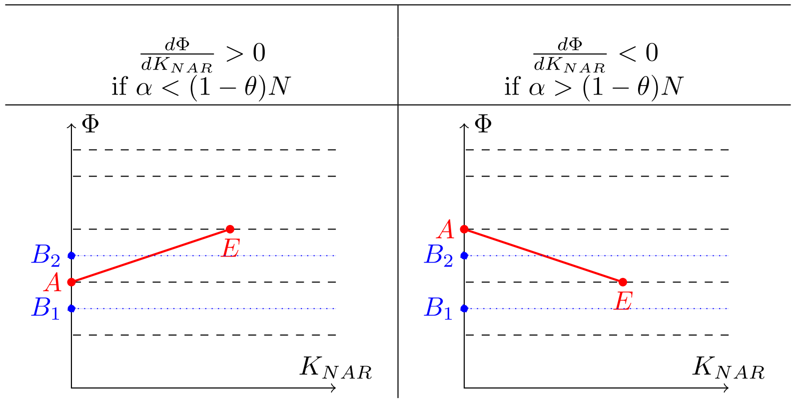

Fig. 1. A graphical representation.

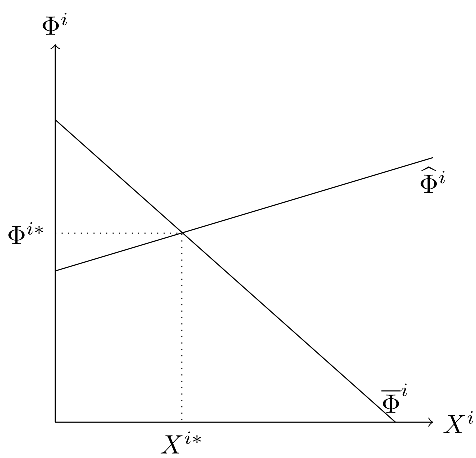

Fig. 2. Equilibrium.

6.3. The optimal scenario for the municipality

The optimal scenario for the municipality can be determined by analyzing the equilibrium graph shown in Fig. 2. In this graph, the constraint of cost coverage ($\widehat{\Phi}^i$, (10a) or (10b)) and the recycling target ($\overline{\Phi}^i$, (11a) or (11b)) are both satisfied when the consumption level is $X^i = X^{i*}$. If the consumption exceeds X^{i*}, the resources collected are not sufficient to cover the cost of the target capital. Conversely, if the consumption is below X^{i*}, there is an excess of tax revenues compared to the cost of capital.

The municipality faces an optimization problem in choosing the appropriate tax rates (τ_C, τ_F) to achieve the equilibrium values of consumption and capital.

Proposition 5. *Let X^{i*} and Φ^{i*} represent the equilibrium values that determine the optimal scenario for a municipality. If $0 < s < b-1$, there exists an infinite set of combinations (τ_C, τ_F) that the municipality can choose, while satisfying the constraint $X^i = X^{i*}$. Within this set, it holds that $\frac{d\tau_F^i}{d\tau_C} < 0$. Conversely, if $s = b-1$, all the tax burden falls on the citizens, resulting in the existence of only one level of τ_C that allows the attainment of this equilibrium.*

Proof. The proof is straightforward by applying the implicit function theorem to the constraint $X^i = X^{i*}$. □

The proposition implies that if the ratio of firms urban waste (s), exogenously set by the government, is within a certain range, the municipality has flexibility in choosing the tax rates for firms and citizens to achieve the equilibrium consumption level. In this range, there are multiple combinations of tax rates that lead to optimal the consumption level that satisfies both constraints. However, if the parameter s reaches its maximum value, it implies that all waste generated by firms is classified as special waste. This means that there is no distinct category for urban waste produced exclusively by firms. As a result, the tax burden is completely transferred to the citizens, and there exists only one tax rate that satisfies the equilibrium condition in this scenario.

Note that taxation on firms and on citizens are strategic substitutes. The choice of tax rates combination depends on the municipality's redistribution goals. If the municipality has no concerns regarding redistribution, it is free to select any combination of taxes, including the option of setting $\tau_F^i = 0$. However, if the municipality aims to redistribute resources towards citizens, it may opt to decrease taxes on citizens while increasing the tax burden on firms. The study of the determinants of the equilibrium consumption level X^* provides insights into the municipality's redistributive goals.

By comparing the costs of Φ^{*AR} and Φ^{*NAR} and considering the specific values of the influencing factors, we can identify the optimal scenario that offers the municipality lower costs and, consequently, lower capital expenditure. Selecting the scenario with lower costs (lower capital) allows the municipality to respect the target on recycling, efficiently allocate resources, optimize waste management processes, and contribute to a more sustainable and economically viable municipality.

From the calculus that we present in Appendix C, we find that

$$\Phi^{*NAR} - \Phi^{*AR} = \sigma \frac{(b-1-s)\theta N}{\sigma c + (1-\theta)N + 1} (\rho(\alpha) - \pi(\alpha)) \tag{12}$$

where

$$\pi(\alpha) = p_R - \frac{\gamma}{1+\alpha},$$

is the profit from recycling and

$$\rho(\alpha) = \begin{cases} \frac{1}{\sigma} & \text{for } \alpha < (1-\theta)N \\ \frac{1}{\sigma}\left(\frac{1+(1-\theta)N}{1+\alpha}\right) & \text{for } \alpha \geq (1-\theta)N \end{cases},$$

is a measure of the impact on target of recycling of the relative productivity of citizens on respect to firms.

Therefore, in order to minimize the cost and respect the target, it is sufficient to compare $\rho(\alpha)$ and $\pi(\alpha)$. In Fig. 3 we represent the threshold, the dashed line is $\rho(\alpha)$ the thick line is $\pi(\alpha)$. From the calculus presented in appendix and Fig. 3, we prove the following propositions

Proposition 6. *There exists a threshold $\bar{\alpha}$ such that, for $\alpha \lesseqqgtr \bar{\alpha}$, $\Phi^{*AR} \lesseqqgtr \Phi^{*NAR}$, for which $\frac{d\bar{\alpha}}{d\sigma} < 0$, $\frac{d\bar{\alpha}}{dp_R} < 0$, $\frac{d\bar{\alpha}}{d\theta} < 0$, and $\frac{d\bar{\alpha}}{d\gamma} > 0$ $\frac{d\bar{\alpha}}{d(1-\theta)N} > 0$.*

Proof. Proof in appendix □

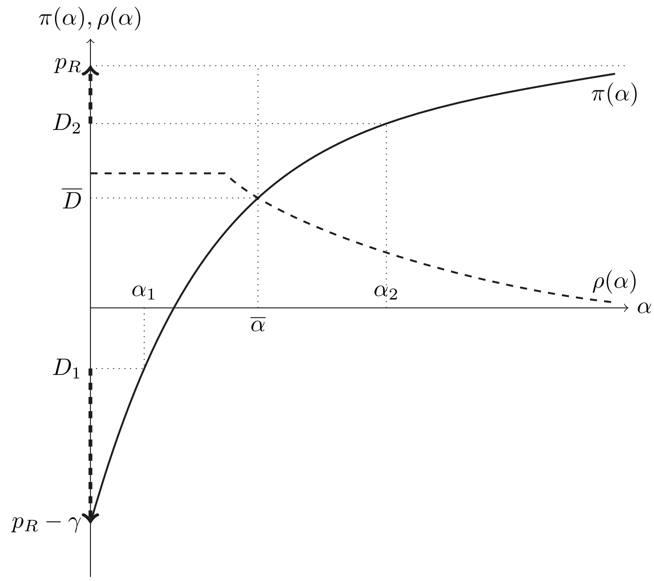

Fig. 3. The threshold for determining the optimal choice of municipality.

This proposition suggests that firms recycling productivity α plays a pivotal role in determining the cost-effective solution for the municipality. The optimal scenario for the municipality entails incentivizing firms with low productivity ($\alpha < \overline{\alpha}$) to opt for autonomous recycling (AR) while encouraging productive firms ($\alpha > \overline{\alpha}$) to choose the municipal waste collector (NAR).

Increasing the threshold value by the municipality ($\overline{\alpha}$) of firms' recycling productivity means that firms with lower productivity levels are not allowed to participate in the municipal waste management system. In this case, only those with higher productivity levels are accepted. Therefore, increasing the threshold value leads to a higher probability that firms choose Autonomous Recycling (AR). Conversely, if the municipality lowers the threshold value, it would increase the likelihood of firms choosing Non-Autonomous Recycling (NAR).

Let us analyze all the factors that influence the threshold value (mentioned in the proposition) and, consequently, the optimal solution for the municipality in waste management.

If the government decides to increase the recycling target (σ), the municipality will need to raise the volume of recycled waste to meet the new target. In response, the municipality may choose to lower the threshold value, allowing low-productivity firms to participate in its waste management system. This decision increases the likelihood of the NAR regime. An increase in citizens' recycling productivity $(1-\theta)$N leads the municipality to raise the threshold value ($\overline{\alpha}$) for firms participating in municipal waste management activities. When citizens dedicate more time to recycling, they contribute to the government's recycling targets more effectively (low θ). This increased citizens participation reduces the overall demand for firms dealing with unproductive waste in the system, prompting the municipality to raise the productivity threshold value. This demonstrates that citizen co-production efforts enhances the recycling capacity of firms accepted into the municipal waste system, underscoring the importance of co-production and civic engagement within the waste management system.

In the scenario where the price of recycling waste paid by private waste collectors (p_R) increases or the unit cost of recycling (γ) decreases, it implies that autonomous recycling becomes more profitable for firms. This increase in profitability leads to a rise in the value added by firms, which is distributed through wages to citizens. Consequently, for a given number of citizens and firms, there is a subsequent increase in the total waste produced within the system. As the total waste generated increases, the probability of the municipality failing to reach the recycling target also rises. To address this situation and improve the likelihood of achieving the recycling target, the optimal choice for the municipality would be to lower the threshold for admission into the waste management system. By accepting even low-productivity firms into the system, the municipality can increase the participation of firms and potentially enhance the overall recycling capacity. Through such channel, private and municipal waste collectors compete for the more productive firms.

The central government decisions have an impact in the optimal choice of the municipality. Note that when central government changes the definition of urban waste modifying s, it does not directly influence the optimal choice of the municipality, but rather affects the magnitude of the incentive associated with this choice.

Proposition 7. *When* $s < b-1$, $\frac{d(\Phi^{*NAR}-\Phi^{*AR})}{ds} \gtreqless 0$ *if* $\Phi^{NAR} - \Phi^{AR} \lesseqgtr 0$. *Moreover* $\Phi^{*NAR} = \Phi^{*AR}$ *if* $s = b-1$.

Proof. Proof in appendix. □

As the value of s increases (while $s < b-1$), the preference for the chosen scenario decreases because the cost difference $|\Phi^{*NAR} - \Phi^{*AR}|$ diminishes, which leads to a reduced preference for the chosen scenario (either AR of NAR). Moreover, when $s = b-1$, meaning that there is no urban waste produced by firms, the municipality becomes indifferent to the scenarios.

6.4. The incentive compatibility solution

The recycling productivity of firms plays a crucial role in determining the optimal choice between firms and the municipality for waste management. More productive firms find it more convenient to opt for a private waste manager (AR) rather than the municipal waste collector (NAR). Conversely, the municipality reaches an optimal solution when productive firms choose its waste management services. This conflicting preference between firms and the municipality creates an incentive compatibility problem that becomes more pronounced as the waste of firms are considered urban (for low s).

Optimal taxation incentives. To address the conflicting preferences between firms and municipality regarding waste management options, the municipality should utilize tax instruments to incentivize firms to choose its optimal waste management scenario.[16] Recalling (5), the incentive-compatible solution must satisfy the following condition: when $\Phi^{*AR} \lesseqgtr \Phi^{*NAR}$ it should also holds $w^{AR} \gtreqless w^{NAR}$. If the municipality would prefer firms to choose AR ($\alpha < \overline{\alpha}$), the tax structure should be set to ensure a higher value added for firms ($w^{AR} > w^{NAR}$). Recalling that firm is indifferent if $D = \tau_F^{AR} - \tau_F^{NAR} = p_R - \frac{\gamma}{1+\alpha}$ and that, for Proposition 1, $\frac{d}{dD}\left(w^{AR} - w^{NAR}\right) \leq 0$. Thus $w^{AR} > w^{NAR}$ can be achieved by ensuring that the difference in taxation between the scenarios $D = \tau_F^{AR} - \tau_F^{NAR}$ satisfies $D < p_R - \frac{\gamma}{1+\alpha}$. Conversely, if the municipality prefers firms to choose its waste services ($\alpha > \overline{\alpha}$), the tax structure should be set such that $w^{AR} < w^{NAR}$. This can be achieved by ensuring that the difference $D = \tau_F^{AR} - \tau_F^{NAR}$ satisfies $D > p_R - \frac{\gamma}{1+\alpha}$. In this case, firms are incentivized to opt for the municipal waste collector.

Generalizing, let us define $\overline{D} = p_R - \frac{\gamma}{1+\overline{\alpha}}$ as in Fig. 3, this is the value of taxes differences for which firms with productivity equal to $\alpha = \overline{\alpha}$ are indifferent between the two scenarios. In other words, when the municipality is indifferent between scenarios, since the firms productivity is $\overline{\alpha}$, if $D = \overline{D}$, also firms would be indifferent between scenarios. Thus the following proposition holds:

[16] If the municipality incurs lower costs when firms opt for a private waste collector, it corresponds to the case of point B_1 ($B_1 \prec A$ or $B_1 \prec E$) on the 1. Conversely, if the municipality incurs higher costs when firms choose a private waste collector, it corresponds to the case of point B_2 ($B_2 \succ A$ or $B_2 \succ E$) on the same graph.

Proposition 8. *If $\alpha < \overline{\alpha}$, there exists a tax difference value $D_1 < \overline{D}$ such that for $D < D_1$, the tax structure is incentive compatible for firms to choose Non-Autonomous Recycling (NAR). Similarly, if $\alpha > \overline{\alpha}$ there exists a tax difference value $D_2 > \overline{D}$ such that for $D > D_2$, the tax structure is incentive compatible for firms to choose Autonomous Recycling (AR). Given a certain level of productivity α, when the price received for recycled waste increases, in order to satisfy the condition of incentive compatibility, also the difference in taxes D has to increases $\frac{dD}{p_R} > 0$.*

Proof. Proof can be deducted immediately from Fig. 3. □

The tax difference D plays a crucial role in influencing firms' decisions regarding waste management options. The municipality has the power to set this tax difference at different levels to achieve specific outcomes.

In the case of low-productivity firms, the municipality aims to encourage firms to choose Autonomous Recycling (AR) over Non-Autonomous Recycling (NAR). To achieve this, the municipality should set the tax difference D at a sufficiently low level (as in Fig. 3, where $D_1 < \overline{D}$), meaning that the tax rate for firms using the private waste management options (τ_F^{AR}) should be lower than the tax rate for firms opting for the municipal waste collector (τ_F^{NAR}). On the other hand, in the case of high-productivity firms, the municipality wants to incentivize firms to choose the municipal waste collector (NAR) as the preferred waste management option. In this scenario, the municipality needs to set the tax difference D at a higher level (as in Fig. 3, $D_2 > \overline{D}$), indicating that ($\tau_F^{AR} > \tau_F^{NAR}$). This higher tax difference makes the municipal waste management services more financially attractive for firms. If the tax incentive is set equal to the price for waste disposal ($D = p_R$), firms will always choose the municipal waste collectors regardless of their productivity. On the other hand, if D is set as the difference between the price for waste disposal and the cost of autonomous recycling ($D = p_R - \gamma$), firms will always choose autonomous recycling, completely avoiding the use of municipal waste collectors.

Indeed, the tax incentive provided by the municipality is influenced not only by the internal dynamics but also by external factors, such as the pricing offered by competitors and the cost of firms' autonomous recycling. When the profit from autonomous recycling increases (reflected by an increase in p_R or a decrease in χ), productive firms are more likely to choose this option instead of the municipal waste collectors. To counteract this preference and encourage productive firms to opt for the municipal waste collectors, the tax burden on firms utilizing this option (τ_F^{NAR}) should be reduced, making the municipal option more financially attractive. As a result, the municipality may increase the tax burden on citizens to compensate for the reduced tax revenue from firms, ensuring that the cost of the municipal waste management system is covered. Conversely, if there is a reduction in the profit from autonomous recycling (a decrease in p_R or an increase in χ), making the AR option less appealing, the municipality may consider reducing the tax incentive provided to firms. Therefore, if the private collectors become less competitive, the municipality can reduce the tax burden on citizens.

Role of central government in the optimal taxation incentives of the municipality. The parameter s, determined by the central government, which represents the proportion of waste categorized as special and has an impact on both firms (Proposition 2) and municipality choices (Proposition 7). To assess the significance of the incentive compatibility problem, we introduce a measure of incentives V, which represents the absolute value of the total incentives provided to firms to ensure minimum waste collection costs for municipalities: $V = \left|\tau_F^{AR} - \tau_F^{NAR}\right| \theta N$. In other words, V quantifies the magnitude of the incentive compatibility problem.

Proposition 9. $\frac{dV}{ds} < 0$ *with* $V = 0$ *when* $s = b - 1$.

Proof. The proof can be demonstrated immediately from Proposition 2. □

As the proportion of waste classified as special (s) increases, the incentive compatibility problem in waste management diminishes. This happens because the economic advantage associated with the preferred choices for both firms and the municipality decreases, leading to a reduce need for incentives. If all waste generated by firms is classified as special (i.e., s reaches the value of $b - 1$), the incentives become unnecessary as the two scenarios become economically equivalent. Thus, V becomes zero, indicating the complete elimination of the incentive compatibility problem.

7. Summary of results and policy implications

The paper models the waste management decisions made by citizens, firms, and municipalities, taking into account the interconnected nature of their behaviors. Findings offer policy implications aimed at promoting sustainable waste management practices and improving recycling outcomes for firms, citizens, municipalities, and the government.

Citizens. The results indicate that both citizens' recycling productivity and their involvement in co-production activities have a notable influence on the optimal solution for citizens, firms, and the municipality. Indeed, increasing citizen involvement and improving their recycling efficiency decrease the municipality's demand for firms generating unproductive waste. Policymakers should focus on promoting public awareness campaigns and fostering a sense of civic responsibility to encourage greater participation in recycling and cleanliness initiatives that can encourage recycling behavior.

Moreover, the model suggests a trade-off between citizens' preference for consumption (θ) and the quantity of waste recycled. Policymakers need to strike a balance between promoting economic growth and meeting citizens' consumption needs while addressing environmental concerns.

Firms. Firms have a choice between Autonomous Recycling (AR) and Non-Autonomous Recycling (NAR) as waste management options, which depends on the comparison between the potential profit/value added obtained from each regime, as well as the presence of fiscal incentives provided by the municipality, taking into account the specific conditions of production function and labor market. The optimal choice for firms depends on their recycling productivity levels and the tax incentives provided by the municipality. Firms with better recycling capabilities tend to opt for autonomous recycling methods rather than relying on municipal waste collectors. Tax incentives can influence firms' waste management choices. Lower taxes for NAR option can incentivize firms to choose that option.

One limitation of our model arises from our assumption that firms are homogeneous. In reality, firms exhibit variations in their recycling productivity, which can influence their waste management decisions. When a single incentive scheme is applied uniformly, some less productive firms may still opt for municipal waste collection, even if the municipality prefers otherwise. Conversely, highly productive firms that the municipality seeks to attract may choose to remain outside the established system. To address this limitation, a more nuanced approach that tailors the incentive structure to accommodate varying levels of firm productivity is necessary. However, the implementation of this differentiated incentive modulation may face technical hurdles or encounter resistance from various stakeholders.

Another limitation of the study is the assumption that the quantity of waste recycled by firms does not depend on the labor force employed for the production of consumption goods. Instead, it relies on the capital. The possibility of allocating both labor and capital to the production of consumption goods and recycled waste adds complexity to the model posing a problem of internal allocation of labor and capital between consumption good and waste,[17] but does not alter the core essence of our model regarding the fact that municipality needs the most performing firms, the incentive compatibility problem and solution that derives from the conflicting interest between municipality and firms.

By considering firms' productivity levels and implementing effective tax incentives, the municipality can encourage firms to adopt sustainable waste management practices and align their choices with the municipality's waste management goals. This collaboration can lead to more efficient waste management, reduced reliance on municipal waste collectors, and improved overall environmental outcomes. However, striking a balance between fairness, effectiveness, and feasibility becomes a key consideration when designing the incentive scheme. Policymakers and stakeholders need to carefully evaluate the trade-offs and determine the most appropriate approach that aligns with the specific context objectives of waste management and incentive schemes.

Municipality. The municipality plays a critical role in waste management and recycling. It has the authority to set policies, regulations, and tax incentives that influence the choices of citizens and firms in waste disposal and recycling methods. The municipality can use tax incentives and pricing mechanisms to steer the behavior of citizens and firms towards desired waste management practices. By adjusting the tax difference (D) between different waste management options, the municipality can incentivize firms to choose specific methods such as Autonomous Recycling (AR) or Non-Autonomous Recycling (NAR). This involves setting the tax difference (D) at levels that promote the optimal choices for firms while also considering the financial viability of the municipal waste management system.

In the model, we do not explicitly consider distributive issues since all the firm's income is distributed to the households. Further analyses can assess the re-distribution challenge that arise when productive firms are incentivized to remain within the urban waste management system. The question of who bears the tax burden and how it affects the ability to incentivize productive firms is indeed a crucial consideration. When lowering taxes for firms to incentivize their participation in the urban management system, it can result in an increased tax burden on citizens. This trade-off between efficiency and equity poses a challenge for the municipality, as they need to strike a balance between encouraging productivity and ensuring a fair distribution of tax burdens. Implementing incentive measures may face resistance from individuals or groups who would experience higher tax burdens, perceiving it as unfair or inequitable. The municipality needs to carefully consider the concerns of different segments of the population and strive for a solution that promotes both productivity and fairness. Addressing this issue requires innovative policy design that considers the interests of all stakeholders involved, including firms, citizens, and the municipality. Stakeholders' engagement is crucial to gather diverse perspectives and ensure that the proposed incentive scheme is acceptable and sustainable in the long run. Furthermore, ongoing evaluation of the impacts and effectiveness of the incentive scheme is necessary to make informed adjustments and optimize the balance between productivity and a fair tax system. This iterative process allows for continuous improvement and adaptation to changing circumstances and stakeholder needs.

The municipality should be flexible and adaptable to changing circumstances, such as shifts in the cost of recycling, market dynamics, or technological advancements. Adjusting tax incentives and regulations accordingly can help align the choices of citizens and firms with evolving waste management goals. The municipality should actively collaborate with citizens and firms in promoting and facilitating co-production initiatives. Co-production activities, where citizens and firms work together with the municipality, can enhance the efficiency, effectiveness, and sustainability of waste management initiatives.

[17] In order to equalize the marginal profit coming from production of consumption goods and from recycling.

Central government. The central government shape the regulatory framework, set recycling targets and define waste categorization. Findings suggest that recycling targets directly affect the municipality's waste management choices and the incentives provided to firms. Higher recycling targets may necessitate adjustments in the threshold value and tax incentives to encourage firms to participate in waste management activities. The government influence with the categorization of waste, including the proportion of waste classified as special waste (parameter s), influences the economic advantage of the firms' choices between AR and NAR, as well as the magnitude of the incentive compatibility problem.

Central government decisions regarding waste categorization can affect the overall efficiency and effectiveness of waste management systems. Therefore these choices should be based on a thorough understanding of local conditions, stakeholder engagement.

Another important task of central government is the definition itself of the target. Our results rely on the assumption that waste from firms sent to private collectors is not considered in the fulfillment of the recycling target set by municipalities. If we include in the target all the waste produced in territory of the municipality, regardless of whether it is collected through the municipal waste manager or a private waste collector the overall results remain unchanged with the case discussed in the text. However, there are a few changes: it is less likely that the municipality would prefer firms to opt for a private collector, and the incentive-compatible tax difference between the two scenarios ($\tau_F^{AR} - \tau_F^{NAR}$) and the cost associated is reduced. Detailed calculations for this alternative target can be found in Appendix D

Co-production. The research emphasizes the significant role of co-production activities in waste management, particularly in recycling, involving both citizens and firms. The findings highlight that the productivity of waste generated by both citizens and firms, which can be attributed to their efforts in co-production, plays a crucial role in determining the optimal waste management solutions for firms, citizens, and the municipality. Furthermore, the active engagement of citizens in co-production activities related to recycling and waste disposal can influence the decision-making of firms regarding their waste management strategies, illustrating the intricate nature of co-production behavior.

Moreover, co-production has implications for the overall cleanliness of the city. When citizens actively participate in waste management activities, such as the proper disposal of special waste, it contributes to maintaining a cleaner environment. This cleanliness has positive effects on firms, the municipality, and the government. A clean city enhances the overall attractiveness and image of the municipality, which can potentially benefit the business operations of firms. Therefore, the involvement of citizens and firms in co-production activities not only fosters effective waste management but also contributes to the overall well-being and success of the municipality.

Various policy implications derive from the findings. Given the vital role of co-production in the waste management system and its potential to drive sustainable solutions for the entire community, it is crucial to actively promote its implementation. Co-production activities require strong support from the municipality or government to thrive and deliver desired outcomes. By actively supporting co-production, the municipality can foster collaboration between citizens, firms, and government entities, creating a synergy that leads to more efficient waste management practices. The municipality can provide financial incentives, educational programs, and logistical support to encourage citizens and firms to actively engage in co-production activities. Furthermore, the municipality should establish clear guidelines and regulations that promote co-production practices, ensuring compliance with environmental standards and fostering a culture of sustainability within the community. By creating an enabling environment for co-production, the municipality can harness the collective efforts of citizens and firms, leading to more sustainable waste management practices and a healthier, cleaner community.

Private waste management. The presence of a private manager as a competitor motivates the municipality to prioritize the productivity of firms. If the municipality fails to provide suitable incentives to firms, the private collector may attract the most efficient firms. Consequently, the municipality becomes more focused on measuring firm performance and implementing innovative strategies to collaborate with them in recycling efforts. This dynamic encourages the municipality to continuously enhance its waste management system and explore innovative approaches to achieve optimal solutions. In this way, competition can serve as a catalyst for the municipality to improve its waste management practices and consistently seek innovative methods.

8. Conclusions

In this study we model through sequential game theory the intricate web of waste management decisions made by citizens, firms, municipalities. Exogenous players are considered the central government and the private waste manager that is the competitor of municipal waste management system. The findings have significant implications that help develop effective waste management policies and promote sustainability.

The study highlights the significance of recycling productivity for both citizens and firms in determining the optimal solution for the municipality. The allocation of recycling capital to citizens and firms is contingent upon their respective productivity levels. If citizens demonstrate higher productivity compared to firms, the municipality may decide that it is optimal not to provide capital to firms. Conversely, evaluating the recycling productivity of firms becomes crucial in identifying those that exceed the optimal threshold, enabling the municipality to achieve its optimal solution. High-performing firms may be preferred by the municipality to collaborate with the municipal waste collector, ensuring efficient waste management. However, high performing firms prefer to dispose their waste to the private waste manager. This creates an incentive compatibility problem, as the municipality should design an appropriate incentive scheme to achieve optimal solutions. As discussed in the previews section, the municipality has to face several challenges in the implementation of these schemes.

Therefore, the municipality should explore methods to enhance the recycling productivity of both citizens and firms to attain a superior optimal solution. Additionally, implementing protocols to measure the productivity of citizens and particularly firms is essential. By understanding the productivity level of recycled waste (α), the municipality can not only monitor the quality of recycled waste within the city but also make informed decisions regarding the optimal solution.

Data availability

No data was used for the research described in the article.

Appendix A. The choice of firms: proof of Propositions 2 and 3

The derivatives of Eq. (4b) are:

$$\frac{dw^{AR}}{dp_R} > 0; \frac{dw^{AR}}{d\gamma} < 0; \frac{dw^{AR}}{d\alpha} > 0; \frac{dw^{AR}}{d\chi} < 0; \frac{dw^{AR}}{dz} > 0; \frac{dw^{AR}}{d\tau_F} < 0.$$

Moreover

$$\frac{dw^{AR}}{ds} \leq 0 \text{ if } \tau_F^{AR} - \chi < \left(p_R - \frac{\gamma}{1+\alpha}\right), \text{ otherwise } \frac{dw^{AR}}{ds} > 0.$$

This means, in case of autonomous recycle, the value added that firms produce decreases with the share of special waste (s) if the unit profit of autonomous recycling is higher than the taxes saved net of the cost for disposing special waste, otherwise the value added increases with s.

The derivatives of Eq. (4c) are:

$$\frac{dw^{NAR}}{dp_R} > 0; \frac{dw^{NAR}}{d\gamma} < 0; \frac{dw^{NAR}}{d\alpha} > 0; \frac{dw^{NAR}}{d\chi} < 0; \frac{dw^{NAR}}{dz} > 0; \frac{dw^{NAR}}{d\tau_F} < 0.$$

Moreover

$$\frac{dw^{NAR}}{ds} \leq 0 \text{ if } \tau_F^{NAR} \leq \chi, \text{ otherwise } \frac{dw^{NAR}}{ds} > 0$$

that is to say, in case of recycling with municipal collector, the value added decreases with s if the tax on a unit of waste is lower than the cost of special waste. If the tax rate is higher, the value added increases.[18]

Since $\frac{d}{ds}\left(w^{AR} - w^{NAR}\right) = -\left(p_R - \frac{\gamma}{1+\alpha} - D\right) = -\frac{w^{AR}-w^{NAR}}{b-1-s}$ and $\frac{d}{db}\left(w^{AR} - w^{NAR}\right) = \left(p_R - \frac{\gamma}{1+\alpha} - D\right) = \frac{w^{AR}-w^{NAR}}{b-1-s}$, we prove Propositions 2 and 3.

Appendix B. The municipality

The first constraint. states that the cost is covered by tax revenues:

$$c\overline{\Phi}^i = \tau_F^i(b-1-s)L^i + \tau_C X^i$$

or

$$\Phi^i = K_C^i + K_{NAR}^i \leq \overline{\Phi}^i = \frac{1}{c}\left[\tau_F^i(b-1-s) + \tau_C \frac{w^i}{1+\tau_C}\right]\theta N$$

where $\frac{d\overline{\Phi}}{d\tau_C} > 0$ and $\frac{d\overline{\Phi}}{d\tau_F} > 0$. Since, $\tau_F^i(b-1-s) = -w^i + (1-\chi s) + r^i\left(p_R - \frac{\gamma}{1+\alpha}\right)$ we obtain

$$\overline{\Phi}^i = \frac{1}{c}\left[-w^i + 1 - \chi s + r^i\left(p_R - \frac{\gamma}{1+\alpha}\right) + \tau_C \frac{w^i}{1+\tau_C}\right]\theta N$$

from this we can calculate (10a) and (10b).

The second constraint. derives from target (8), from which we may calculate the target level of waste recycled by citizen is

$$\hat{R}_C^i = \sigma\left(WST_X^i + WST_F^i + R_F^i\right) - R_F^i$$

Thus, the second constraint concerning the target of waste is $R_C^i \geq \hat{R}_C^i$. Recalling that in scenario (NAR), all the waste which firms are responsible of is collected by municipality, then $WST_{NAR} = R_F^{NAR}$ and $WST_{NAR} + WST_F^{NAR} = (b-1-s)\theta N$. Moreover $R_F^{NAR} = (1+\alpha)K_{NAR}$. On the contrary in the scenario (AR), $R_F^{AR} = 0$ and $WST_{AR} + WST_F^{AR} = 0$, we have:

$$\begin{aligned}\hat{R}_C^{NAR} &= \sigma\left[\frac{w^{NAR}}{1+\tau_C} + (b-1-s)\right]\theta N - (1+\alpha)K_{NAR}, \\ &= \sigma X^{NAR} + \sigma\theta(b-1-s)N \\ &\text{with } (1+\alpha)K_{NAR} \leq (b-1-s)\theta N \\ \hat{R}_C^{AR} &= \sigma\left[\frac{w^{AR}}{1+\tau_C}\right]\theta N = \sigma X^{AR}.\end{aligned}$$

Recalling the optimal recycling chosen by citizen (Eq. (7b)) we can calculate the constraint on target in term of capital:

$$K_C[(1-\theta)N + 1] \geq \sigma X^{NAR} + (b-1-s)\theta N - (1+\alpha)K_{NAR} + \frac{1}{\beta},$$

$$\begin{aligned}K_C &\geq \sigma\frac{X^{NAR}}{(1-\theta)N+1} + (b-1-s)\frac{\theta N}{(1-\theta)N+1} \\ &\quad - (1+\alpha)\frac{K_{NAR}^i}{(1-\theta)N+1} + \frac{1}{[(1-\theta)N+1]\beta} \\ \Phi^{NAR} \geq \hat{\Phi}^{NAR} &= \sigma\frac{X^{NAR}}{(1-\theta)N+1} + (b-1-s)\frac{\theta N}{(1-\theta)N+1} \\ &\quad + \frac{(1-\theta)N-\alpha}{(1-\theta)N+1}K_{NAR} + \frac{1}{[(1-\theta)N+1]\beta} \\ &\quad \text{with } (1+\alpha)K_{NAR} \leq (b-1-s)\theta N\end{aligned}$$

[18] Note that, if the unit profit of autonomous recycling $\left(p_R - \frac{\gamma}{1+\alpha}\right)$ is greater than 0, the condition for having $\frac{dw^{NAR}}{ds} \leq 0$ is more binding in case of NAR than of AR, if negative is less binding.

$$\Phi^{AR} \geq \hat{\Phi}^{AR} = \sigma \frac{X^{AR}}{(1-\theta)N+1} + \frac{1}{[(1-\theta)N+1]\beta}.$$

from which we obtain Eqs. (11a) and (11b).

Appendix C. The optimal scenario and the incentive compatible taxes: proof of Propositions 6 and 7

Considering both constraint, in case of AR scenario the first constraint (Eq. (10a)) can be written as:

$$c\Phi^{AR} + X^{AR} = \left[1 - \chi s + \left(p_R - \frac{\gamma}{1+\alpha}\right)(b-1-s)\right]$$

The second constraint (Eq. (11a)) can be written as:

$$[(1-\theta)N+1]\,\Phi^{AR} - \sigma X^{AR} = \frac{1}{\beta}.$$

writing them in matrix form.

$$\begin{pmatrix} c & 1 \\ (1-\theta)N+1 & -\sigma \end{pmatrix}\begin{pmatrix} \Phi^{AR} \\ X^{AR} \end{pmatrix} = \begin{pmatrix} \left[1-\chi s + \left(p_R - \frac{\gamma}{1+\alpha}\right)(b-1-s)\right]\theta N \\ \frac{1}{\beta} \end{pmatrix}$$

$$\begin{pmatrix} \Phi^{AR} \\ X^{AR} \end{pmatrix} = \frac{1}{\sigma c + (1-\theta)N+1}\begin{pmatrix} \sigma & 1 \\ (1-\theta)N+1 & -c \end{pmatrix} * \begin{pmatrix} \left[1-\chi s + \left(p_R - \frac{\gamma}{1+\alpha}\right)(b-1-s)\right]\theta N \\ \frac{1}{\beta} \end{pmatrix}$$

In case of NAR, we have to compute the constraint firstly in case of low productive firms, then in case of high productive ones.

In the first case, $K_{NAR} = 0$

$$\begin{pmatrix} c & 1 \\ (1-\theta)N+1 & -\sigma \end{pmatrix}\begin{pmatrix} \Phi^{NAR} \\ X^{NAR} \end{pmatrix} = \begin{pmatrix} [1-\chi s]\,\theta N \\ (b-1-s)\theta N + \frac{1}{\beta} \end{pmatrix}$$

then

$$\begin{pmatrix} \Phi^{NAR} \\ X^{NAR} \end{pmatrix} = \frac{1}{\sigma c + (1-\theta)N+1}\begin{pmatrix} \sigma & 1 \\ (1-\theta)N+1 & -c \end{pmatrix} * \begin{pmatrix} [1-\chi s]\,\theta N \\ (b-1-s)\theta N + \frac{1}{\beta} \end{pmatrix}.$$

In the second case, $\left(\alpha > (1-\theta)N \Rightarrow K_{NAR} = \frac{(b-1-s)\theta N}{1+\alpha}\right)$

$$\begin{pmatrix} \Phi^{NAR} \\ X^{NAR} \end{pmatrix} = \frac{1}{\sigma c + (1-\theta)N+1}\begin{pmatrix} \sigma & 1 \\ (1-\theta)N+1 & -c \end{pmatrix} * \begin{pmatrix} [1-\chi s]\,\theta N \\ (b-1-s)\theta N\frac{1+(1-\theta)N}{1+\alpha} + \frac{1}{\beta} \end{pmatrix}$$

thus let we calculate the difference among scenarios.

When firms are less productive then citizens

$$\begin{pmatrix} \Phi^{NAR} - \Phi^{AR} \\ X^{NAR} - X^{AR} \end{pmatrix} = \frac{1}{\sigma c + (1-\theta)N+1}\begin{pmatrix} \sigma & 1 \\ (1-\theta)N+1 & -c \end{pmatrix} * \begin{pmatrix} -\left(p_R - \frac{\gamma}{1+\alpha}\right)(b-1-s)\theta N \\ (b-1-s)\theta N \end{pmatrix}.$$

When firm are more productive than citizens $\left(\frac{1+(1-\theta)N}{1+\alpha}\right) \leq 1$

$$\begin{pmatrix} \Phi^{NAR} - \Phi^{AR} \\ X^{NAR} - X^{AR} \end{pmatrix} = \frac{1}{\sigma c + (1-\theta)N+1}\begin{pmatrix} \sigma & 1 \\ (1-\theta)N+1 & -c \end{pmatrix} * \begin{pmatrix} -\left(p_R - \frac{\gamma}{1+\alpha}\right)(b-1-s)\theta N \\ (b-1-s)\theta N\frac{1+(1-\theta)N}{1+\alpha} \end{pmatrix}$$

$\Phi^{NAR} - \Phi^{AR} > 0$ if

$$-\sigma\left(p_R - \frac{\gamma}{1+\alpha}\right) + 1 > 0$$

when $\left(\frac{1+(1-\theta)N}{1+\alpha}\right) > 1$ and if

$$-\sigma\left(p_R - \frac{\gamma}{1+\alpha}\right) + \left(\frac{1+(1-\theta)N}{1+\alpha}\right) > 0$$

when $\left(\frac{1+(1-\theta)N}{1+\alpha}\right) \leq 1$.

From the above calculus, we can derive the general formula for the difference $\Phi^{NAR} - \Phi^{AR} > 0$, that we use in the main text as (12). Let us note that $\pi(0) = p_R - \gamma < 0$, and $\lim_{\alpha=+\infty} \pi(\alpha) = p_R$. Moreover, $\rho(0) = \frac{1}{\sigma}$, $\lim_{\alpha=+\infty} \rho(\alpha) = 0$.

From the above calculus, we derive Fig. 3. Since $\rho(\alpha)$ is decreasing in α and $\pi(\alpha)$ is increasing, the unique threshold $\overline{\alpha}$ exists. Applying the implicit function theorem

$$\frac{d\overline{\alpha}}{d\sigma} < 0,\ \frac{d\overline{\alpha}}{dp_R} < 0,\ \frac{d\overline{\alpha}}{d\theta} < 0,\ \frac{d\overline{\alpha}}{d\gamma} > 0,\ \frac{d\overline{\alpha}}{d(1-\theta)N} > 0.$$

Proposition 6 is proved.

Finally, deriving Eq. (12),

$$\frac{d}{ds}(\Phi^{NAR} - \Phi^{AR}) = -\frac{\Phi^{NAR} - \Phi^{AR}}{b-1-s},$$

Proposition 7 is proved.

Appendix D. Alternative target constraint

(8) defines the percentage that municipal collector has to recycle. It is possible to consider a different target, in which the objective of recycling is not the waste collected through municipal waste manager but all the waste collected in municipality, regardless if through municipal or private waste collector. In this case, we can re-write the target as:

$$\sigma = \frac{R_C^i + r^i L^i + R_F^i}{WST_X^i + r^i Y + R_F^i + WST_F^i} \tag{13}$$

where we recall that $r^{AR} = b-1-s$, all waste produced are recycled in scenario $i = AR$, while $r^{NAR} = 0$. Therefore in scenario AR

$$\sigma = \frac{R_C^{AR} + (b-1-s)\theta N}{WST_X^{AR} + (b-1-s)\theta N},$$

in scenario NAR

$$\sigma = \frac{R_C^{NAR} + R_F^{NAR}}{WST_X^{NAR} + (b-1-s)\theta N}.$$

The target constraint (11a) and (11b) are modified as:

$$\Phi^{AR} \geq \widetilde{\Phi}^{AR} = \sigma\frac{X^{AR}}{(1-\theta)N+1} + (\sigma-1)\frac{(b-1-s)\theta N}{(1-\theta)N+1} + \frac{1}{\beta}\frac{1}{(1-\theta)N+1}$$

$$\Phi^{NAR} \geq \widetilde{\Phi}^{NAR} = \sigma\frac{X^{NAR}}{(1-\theta)N+1} + \sigma\frac{(b-1-s)\theta N}{(1-\theta)N+1} + \frac{1}{\beta}\frac{1}{(1-\theta)N+1} + \frac{(1-\theta)N-\alpha}{(1-\theta)N+1}K_{NAR}$$

Since, for each value of X^i, $\widetilde{\Phi}^i < \hat{\Phi}^i$, the equilibrium pair depicted in Fig. 2 will be $(\widetilde{X}^{i*}, \widetilde{\Phi}^{i*})$ where $X^{i*} < \widetilde{X}^{i*}$ and $\Phi^{i*} > \widetilde{\Phi}^{i*}$, therefore the cost payed by municipality and the tax revenue to cover such a cost are lower. In this case, when we compare the two scenarios, instead of $\rho(\alpha)$ we have $\widetilde{\rho}(\alpha) < \rho(\alpha)$

$$\widetilde{\rho}(\alpha) = \begin{cases} \frac{1}{\sigma} & \text{for } \alpha < (1-\theta)N \\ \frac{1}{\sigma}\left(\frac{1+(1-\theta)N}{1+\alpha}\right) - \frac{\alpha-(1-\theta)N}{1+\alpha} & \text{for } \alpha \geq (1-\theta)N, \end{cases}$$

with $\lim_{\alpha\to+\infty} \widetilde{\rho}(\alpha) = -\infty$.

The following proposition holds

Proposition 10. *When the waste recycled thorough a private collector is included in the calculus of the target, $\exists\widetilde{\alpha} < \overline{\alpha}$ such that for $\alpha \lesseqgtr \widetilde{\alpha}$, $\widetilde{\Phi}^{AR} \lesseqgtr \widetilde{\Phi}^{NAR}$. Moreover, moreover the incentive compatible tax structure in order to convince firms with productivity $\alpha > \widetilde{\alpha}$ is lower than in the case presented in Proposition 8.*

Proof. In order to compare the two scenarios, we express the constraint in matrix form

$$\begin{pmatrix} \Phi^{AR} \\ X^{AR} \end{pmatrix} = \frac{1}{\sigma c + (1-\theta)N + 1} \begin{pmatrix} \sigma & 1 \\ (1-\theta)N + 1 & -c \end{pmatrix} * \begin{pmatrix} \left[1 - \chi s + \left(p_R - \frac{\gamma}{1+\alpha}\right)(b-1-s)\right]\theta N \\ \frac{1}{\beta} + (\sigma - 1)(b-1-s)\theta N \end{pmatrix}$$

In case firms are less productive than citizens $K_{NAR} = 0$, then

$$\begin{pmatrix} \Phi^{NAR} \\ X^{NAR} \end{pmatrix} = \frac{1}{\sigma c + (1-\theta)N + 1} \begin{pmatrix} \sigma & 1 \\ (1-\theta)N + 1 & -c \end{pmatrix} * \begin{pmatrix} \left[1 - \chi s\right]\theta N \\ \sigma(b-1-s)\theta N + \frac{1}{\beta} \end{pmatrix}.$$

In the second case, $\left(\alpha > (1-\theta)N \Rightarrow K_{NAR} = \frac{(b-1-s)\theta N}{1+\alpha}\right)$

$$\begin{pmatrix} \Phi^{NAR} \\ X^{NAR} \end{pmatrix} = \frac{1}{\sigma c + (1-\theta)N + 1} \begin{pmatrix} \sigma & 1 \\ (1-\theta)N + 1 & -c \end{pmatrix} * \begin{pmatrix} \left[1 - \chi s\right]\theta N \\ (\sigma+1)(b-1-s)\theta N \frac{1+(1-\theta)N}{1+\alpha} + \frac{1}{\beta} \end{pmatrix}$$

Taking the differences among scenarios, when firms are less productive then citizens

$$\begin{pmatrix} \Phi^{NAR} - \Phi^{AR} \\ X^{NAR} - X^{AR} \end{pmatrix} = \frac{1}{\sigma c + (1-\theta)N + 1} \begin{pmatrix} \sigma & 1 \\ (1-\theta)N + 1 & -c \end{pmatrix} * \begin{pmatrix} -\left(p_R - \frac{\gamma}{1+\alpha}\right)(b-1-s)\theta N \\ (b-1-s)\theta N \end{pmatrix}.$$

When firm are more productive than citizens $\left(\frac{1+(1-\theta)N}{1+\alpha}\right) \leq 1$

$$\begin{pmatrix} \Phi^{NAR} - \Phi^{AR} \\ X^{NAR} - X^{AR} \end{pmatrix} = \frac{1}{\sigma c + (1-\theta)N + 1} \begin{pmatrix} \sigma & 1 \\ (1-\theta)N + 1 & -c \end{pmatrix} * \begin{pmatrix} -\left(p_R - \frac{\gamma}{1+\alpha}\right)(b-1-s)\theta N \\ (b-1-s)\theta N \frac{(\sigma+1)[1+(1-\theta)N] - \sigma(1+\alpha)}{1+\alpha} \end{pmatrix}$$

$$= \frac{1}{\sigma c + (1-\theta)N + 1} \begin{pmatrix} \sigma & 1 \\ (1-\theta)N + 1 & -c \end{pmatrix} * \begin{pmatrix} -\left(p_R - \frac{\gamma}{1+\alpha}\right)(b-1-s)\theta N \\ (b-1-s)\theta N \sigma \frac{[(1-\theta)N - \alpha]}{1+\alpha} + (b-1-s)\theta N \frac{1+(1-\theta)N}{1+\alpha} \end{pmatrix}$$

From this calculus, we may derive the function $\hat{\rho}(\alpha)$ and therefore we proved Proposition 10. □

References

[1] Hall David, Nguyen Tue Anh. Waste management in europe: companies, structure and employment. European Public Service Union; 2012, http://www.epsu.org/sites/default/files/article/files/2012_Waste_mngt_EWC.pdf.

[2] Directive 2018/851/EU. Directive 851 of the European parliament and of the council of 30 may 2018 amending directive 2008/98/EC on waste. European Parliament; 2018, URL http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0851&rid=5.

[3] Fusco Elisa, Allegrini Veronica. The role of spatial interdependence in local government cost efficiency: An application to waste Italian sector. Socio-Econmic Plan Sci 2020;69:100681.

[4] Cavicchia Carlo, Sarnacchiaro Pasquale, Vichi Maurizio. A composite indicator for the waste management in the EU via hierarchical disjoint non-negative factor analysis. Socio-Econmic Plan Sci 2021;73:100832.

[5] Tafuro Alessandra, Dammacco Giuseppe, Esposito Paolo, Mastroleo Giovanni. Rethinking performance measurement models using a fuzzy logic system approach: A performative exploration on ownership in waste management. Socio-Econmic Plan Sci 2022;79:101092.

[6] Agovino Massimiliano, Casaccia Mariaconcetta, Crociata Alessandro, Sacco Pier Luigi. European regional development fund and pro-environmental behaviour. The case of Italian separate waste collection. Socio-Econmic Plan Sci 2019;65:36–50.

[7] Directive 2008/98/EC. Directive 98 of the European parliament and of the council of 19 november 2008 on waste and repealing certain directives. Off J Eur Un 2008. URL http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32008L0098.

[8] Cohen Chen, Halfon Einat, Schwartz Moshe. Trust between municipality and residents: A game-theory model for municipal solid-waste recycling efficiency. Waste Manag 2021;127:30–6.

[9] Di Liddo Giuseppe, Vinella Annalisa. Co-production in local public service delivery: The case of waste management. BE J Econ Anal Policy 2020;20(4).

[10] Redmond Janice, Walker Elizabeth, Wang Calvin. Issues for small businesses with waste management. J Environ Manag 2008;88(2):275–85.

[11] Du Lei, Feng Yingbin, Lu Wei, Kong Lingkai, Yang Zhi. Evolutionary game analysis of stakeholders' decision-making behaviours in construction and demolition waste management. Environ Impact Assess Rev 2020;84:106408.

[12] Choe Chongwoo, Fraser Iain. An economic analysis of household waste management. J Environ Econ Manag 1999;38(2):234–46.

[13] Tan Y, Guo C. Research on two-way logistics operation with uncertain recycling quality in government multi-policy environment. Sustainability 2019;11(3):882.

[14] Cohen Chen, Halfon Einat, Schwartz Moshe. Trust between municipality and residents: A game-theory model for municipal solid-waste recycling efficiency. Waste Manag 2021;127:30–6.

[15] Directive 1999/31/EC. Council directive 31 of 26 april 1999 on the landfill of waste. 1999, URL http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31999L0031.

[16] Directive 2019/904/EU. Directive 904 of the European parliament and of the council of 5 june 2019 on the reduction of the impact of certain plastic products on the environment. 2019, URL http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32019L0904.

[17] Directive 94/62/EC. Directive 62 European parliament and council directive 94/62/EC of 20 december 1994 on packaging and packaging waste. 1994, URL http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A01994L0062-20180704.

[18] European Commission. Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions a new circular economy action plan for a cleaner and more competitive Europe. 2022, URL http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN.

[19] European Environmental Agency. Municipal waste management across European countries. 2022, URL http://www.eea.europa.eu/publications/municipal-waste-management-across-european-countries/copy_of_municipal-waste-management-across-european-countries.

[20] European Parliament. Waste management in the EU: Infographic with facts and figures. 2023, URL http://www.europarl.europa.eu/news/en/headlines/society/20180328STO00751/waste-management-in-the-eu-infographic-with-facts-and-figures#:~:text=Recycling%2C%20composting%20and%20incineration%20trends,of%20municipal%20waste%20by%202030.

[21] Bartelings Heleen, Sterner Thomas. Household waste management in a Swedish municipality: Determinants of waste disposal, recycling and composting. Environ Res Econ 1999;13:473–91.

[22] Bueno Matheus, Valente Marica. The effects of pricing waste generation: A synthetic control approach. J Environ Econ Manag 2019;96:274–85.

[23] Pfister Naomi, Mathys Nicole A. Waste taxes at work: Evidence from the canton of vaud in Switzerland. Ecol Econom 2022;193:107314.

[24] Saladié Òscar, Santos-Lacueva Raquel. The role of awareness campaigns in the improvement of separate collection rates of municipal waste among university students: A causal chain approach. Waste Manag 2016;48:48–55.

[25] Miltojević Vesna, Ilić Krstić Ivana, Petković A. Informing and public awareness on waste separation: A case study of the city of Niš (Serbia). Int J Environ Sci Technol 2017;14:1853–64.

[26] Massari Sonia, Principato Ludovica, Antonelli Marta, Pratesi Carlo Alberto. Learning from and designing after pandemics. CEASE: A design thinking approach to maintaining food consumer behaviour and achieving zero waste. Socio-Econmic Plan Sci 2022;82:101143.

[27] ISPRA. Rapporto rifiuti Urbani. 2020, URL http://www.isprambiente.gov.it/files2020/pubblicazioni/rapporti/rapportorifiutiurbani_ed-2020_n-331-1.pdf.

[28] Nunes KRA, Mahler CF, Valle R, Neves C. Evaluation of investments in recycling centres for construction and demolition wastes in Brazilian municipalities. Waste Manag 2007;27(11):1531–40.

[29] Leitmeyer Katrin, Buchholz Udo, Kramer Michael, Schenkel Karl, Stahlhut Heike, Köllstadt Michael, Haas Walter, Meyer Christiane. Influenza vaccination in German health care workers: Effects and findings after two rounds of a nationwide awareness campaign. Vaccine 2006;24(47–48):7003–8.

[30] Alford John. A public management road less travelled: Clients as co-producers of public services. Aust J Public Adm 1998;57(4):128–37.

[31] Pestoff Victor, Brandsen Taco. Public governance and the third sector: opportunities for co-production and innovation?. Citeseer; 2010.

[32] Voorberg William H, Bekkers Viktor JJM, Tummers Lars G. A systematic review of co-creation and co-production: Embarking on the social innovation journey. Publ Manag Rev 2015;17(9):1333–57.

[33] Osborne Stephen P, Strokosch Kirsty. It takes two to Tango? Understanding the c o-production of public services by integrating the services management and public administration perspectives. Br J Manag 2013;24:S31–47.

[34] Landi Stefano, Russo Salvatore. Co-production 'thinking'and performance implications in the case of separate waste collection. Publ Manag Rev 2022;24(2):301–25.

[35] Alonso José M, Andrews Rhys, Clifton Judith, Diaz-Fuentes Daniel. Factors influencing citizens' co-production of environmental outcomes: a multi-level analysis. Publ Manag Rev 2019;21(11):1620–45.

[36] Kirakozian Ankinee. The determinants of household recycling: Social influence, public policies and environmental preferences. Appl Econ 2016;48(16):1481–503.

[37] Wang Zhen, Huo Jiazhen, Duan Yongrui. The impact of government incentives and penalties on willingness to recycle plastic waste: An evolutionary game theory perspective. Front Environ Sci Eng 2020;14:1–12.

[38] Di Liddo Giuseppe, Vinella Annalisa. Centralized standards and local taxation in municipal waste management. Ann Public Coop Econ 2021;92(4):603–19.

[39] Czajkowski Mikołaj, Hanley Nick, Nyborg Karine. Social norms, morals and self-interest as determinants of pro-environment behaviours: The case of household recycling. Environ Res Econ 2017;66:647–70.

[40] Minelgaitė Audronė, Liobikienė Genovaitė. The problem of not waste sorting behaviour, comparison of waste sorters and non-sorters in European union: Cross-cultural analysis. Sci Total Environ 2019;672:174–82.

Fabio Fiorillo is Professor of Public Economics and Finance, Economics of Taxation, Health Economics at Università Politecnica delle Marche. Expert appointed by Italian Ministry of the Interior for the ''Osservatorio per la finanza locale e la contabilità pubblica''. Scientific coordinator of IFEL research project: ''La programmazione strategica dei Comuni e gli indici di benessere a livello locale''. He teaches microeconomics in the doctoral program courses at Università Politecnica delle Marche. He is member of SIE (Società Italiana degli Economisti) SIEP (Società Italiana di Economia Pubblica), of AIEL (Associazione Italiana Economisti del Lavoro) and of EALE (European Association Labour Economics).

Elvina Merkaj holds the position of assistant professor of Public Finance at the Polytechnic University of Marche, Italy. She has authored publications in prestigious journals such as the Cambridge Journal of Economy and Society, International Tax and Public Finance, among others. Her research primarily revolves around public finance matters, with a specific emphasis on local governance.