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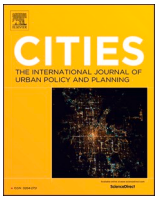

# Factors influencing the rate of sorted solid waste collection: An empirical analysis towards local management in Catalonia (NE Spain)

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ABSTRACT

A study of the factors influencing waste sorting behaviours is crucial to assess the current urban waste management schemes and to determine additional, appropriate policies to put in place. While there exist many theoretical considerations on which factors determine the Sorted Municipal Solid Waste Collection (SMSWC) rates, these are sometimes ambiguous, and firm empirical confirmation is often lacking. The present study estimates econometric models based on a comprehensive set of longitudinal data for all 945 Catalonian municipalities from 2000 to 2019. We demonstrate and quantify geographic, demographic, socioeconomic, and policy design determinants of the SMSWC rates at a municipal level. New insights are obtained on the effects of geographic conditions, unemployment, and foreign population on waste management behaviours, sometimes in direct contradiction with earlier theoretical expectations. The empirical evidence suggests that active waste collection policies can serve to increase the rate of sorted waste collection rapidly enough to achieve the recycling goals set by the European Union legislation and the Spanish Waste Law. Additionally, the study highlights the importance of considering demographic trends and differences in waste sorting behaviour between social groups when tackling waste management issues. The main qualitative results are expected to be valid beyond the concrete case of Catalonia.

## 1. Introduction

Waste sorting, as we know it today, has been around for almost a century. Since World War II, when the U.S. government encouraged citizens to salvage materials for the war (Cooper, 2008), there have been initiatives to reuse waste. However, since single-use items hit the market in the 1950s, these initiatives have consistently fallen short. The environmental, health, and economic benefits of recycling in cities have long been recognized. For instance, Craighill and Powell (1996) combined a life-cycle assessment with an economic valuation technique in a case study of the city of Milton Keynes (Central England), concluding that recycling (recovery of materials and their subsequent use in new products) generally contributes less to global warming, acidification effects, and nutrification of surface water, than waste disposal (landfill disposal of waste and use of primary materials). More recently, Ferreira et al. (2014) carried out a similar study in Portugal and concluded that the total economic and environmental benefits of the packaging waste management systems established in the country exceed the costs. Although waste management has become a challenge for cities, it has also become an opportunity for their economies. The collection, sorting, and processing of waste create jobs and contribute to tax revenue (EPA, 2020). According to an environmental study conducted in Spain, the waste management and processing sector employed 140,000 people nationally in 2009, 279 % more than in 1998 (Fundación Forum Ambiental, 2011).

Urban waste management lies in the administrative and organizational government structures at the local, regional, national, and even international level (Gandy, 2014). Multilevel governance requires precise information to allocate resources and establish policies responsibly. Yet, acquiring this information is challenging due to demographic and socioeconomic characteristics that change swiftly. For example, the phenomenon of urbanization is one of these characteristics, and it has become crucial for waste management planning. As urban areas increase in size, the collection and transportation of waste become more difficult, especially if cities have grown with inadequate planning (Chandrappa & Das, 2012). In this challenging context, better planned waste management practices are needed in cities. To support this planning, it is crucial to understand the factors influencing the Sorted Municipal Solid Waste

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Collection (SMSWC) rates in the cities and their surrounding areas. Concretely, empirical confirmation of the effect of these factors is necessary, and so far largely lacking.

Within the context of increasing urbanization described above, European metropolises serve as a case in point. Europe, together with some Asian countries such as South Korea and Singapore, plays a leading role in the global ecological transformation, particularly in urban waste sorting and recycling (Clémençon, 2016). European policymakers focus on reducing the environmental impact of waste management through the 2030 Agenda for Sustainable Development, with the ultimate objective of improving citizens' life quality and protecting natural resources (Boto-Álvarez & García-Fernández, 2020; Lemaire & Limbourg, 2019). In this sense, specific policies are designed to efficiently reduce urban contamination and limit its impact on climate change and the environment (Amicarelli & Bux, 2021; Principato et al., 2021). The rate of recycling in the European Union has increased 154 % from 1995 to 2019. Yet, only 47.7 % of the Municipal Solid Waste (MSW) was recycled in 2019 (European Statistical Office, 2021). Spain, in the same year, recycled 34.7 % of the MSW. Only two of its Autonomous Communities (AC), Catalonia and the Valencian Community, reached the recycling goal of 50 % set by the Waste Law (BOE, 2011).

Located in the northeast of Spain, Catalonia is the AC with the fourth largest GDP per capita in Spain (INE, 2021) and its capital, Barcelona, is the fifth largest city in the European Union (European Statistical Office, 2022). As of 2021, there are 212 cities with >5000 inhabitants in Catalonia, of which 23 have >100,000 citizens. The region has faced an urbanization process in the last 20 years with an increasing number of cities of between 10,000 and 50,000 inhabitants (Idescat, 2021b). The region's economic activity is characterised by late industrialization, the relevance of traditional services such as construction and commerce, and the growth of tourism as the main economic sector, while the hinterland maintains a strong dependence on agrarian activities. The economic structure of Catalonia, together with deregulated urban growth, presents a challenge for local administrations, and for waste management in particular (Cuadrado-Ciuraneta et al., 2017). These characteristics make Catalonia an exemplary local case to understand waste sorting determinants, and how policies and social phenomena affect these determinants.

The case of Catalonia is far from unique. A region with a bustling metropolis surrounded by smaller cities recently smeared out into de facto urban sprawl is now common in Southern Europe. A similar description is valid for Rome or Naples in Italy, Lisbon or Porto in Portugal, Athens or Thessaloniki in Greece, and to a large extent even Marseille in the South of France, or Split in Croatia. In this sense, the present research is meant as a microcosmos with a complexity representative for much of current Southern Europe. Because of the worldwide trend towards urbanization and Europe's ecological ambitions, Catalonia serves as a relevant example for the future of many regions in the world. Pragmatically, Catalonia is a good case study candidate because there is extensive and easily accessible data of the region. Data on waste collection and on demographic, geographic, and socioeconomic variables, are collected and published by the Catalonian administration and several statistical agencies. However, an important data limitation is that the financial aspects of urban management, such as collection, transportation, and processing costs, are not publicly available. Thus, these are left out of the present study, even though spatial cost-effectiveness is a crucial aspect of waste policy design (e.g., Hage & Söderholm, 2008).

The overall aim of the current paper is to determine and analyse the socioeconomic as well as demographic and geographical factors affecting the management of waste in cities and their surrounding areas. The concrete objective lies in the factors relevant for the Sorted Municipal Solid Waste Collection (SMSWC) rates. A number of variables previously discussed in the academic literature will be studied. These variables have been identified as relevant for SMSWC mostly at the theoretical level. If the literature reflects agreement on the impact (positive or negative) of a variable, our theoretical expectation will be to provide the direly needed empirical confirmation. This statistical confirmation is based on the comprehensive longitudinal database analysis presented below. There are several variables for which there is no agreement in the literature. In those cases, we will test whether the given variable is relevant, and whether its impact is positive or negative. A second objective of this study is to identify how public policy and urban waste management strategies influence these relevant factors, and in particular whether an active public policy could be hoped to dominate over all the other categories of variables. The previous considerations about Catalonia's complex geographic and socioeconomic structure strengthen our confidence that the results are qualitatively valid beyond the concrete example of this particular region, as we hope will be confirmed by future research.

To analyse the multi-layered question posed above quantitatively, a comprehensive analysis capable of capturing the different waste management practices and results in the region is required. From a methodological point of view, the technique by excellence for such an extensive and detailed analysis consists of econometric models. In particular, our analysis is carried out on longitudinal data at the municipal level in Catalonia, spanning twenty years (2000–2019). The use of panel data allows understanding the given heterogeneity separately, through time and across different municipalities. By isolating and assessing the different demographic and policy-related characteristics, it is possible to provide recommendations tailored to each of them. Thus, the main contribution of this study lies in the comprehensive methodology, and its application to a large spatial spectrum of data over a long period of time. Moreover, the results are paradigmatic for Southern Europe, and possibly large parts of the world. We will come back to these differentiators and compare them with the existing literature in the next Section.

Before delving into the study, the following remarks with respect to Catalonia and its waste management policy might be relevant. Catalonia is one of the two ACs with the highest rate of SMSWC in Spain. However, the complexity of its geographical and socio-political structure manifests in a large heterogeneity of selective MSW rates between its municipalities, as it can be observed in Fig. 1. This heterogeneity poses a challenge in devising sustainable urban planning. Analysing urban waste collection rates not only implies understanding the waste sorting behaviour of the households, but also the behaviour of the local governments and the companies responsible for collecting waste.

The jurisdictional division of waste management within Catalonia is

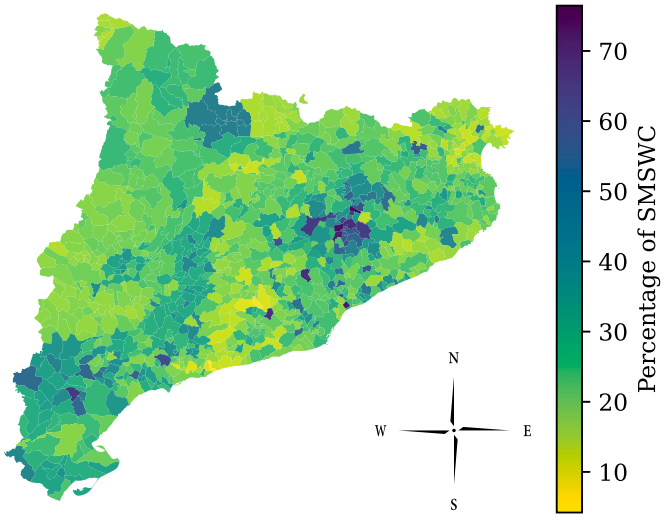


**Fig. 1.** Average selective Municipal Solid Waste collection rate in 945 municipalities of Catalonia, 2000–2019.
(Source: DOC (2021a).)

structured as follows. Waste sorting and processing policy goals in Spain are devised at the national level, but the ACs are responsible for monitoring, inspecting, and sanctioning the MSW production and processing activities (BOE, 2011). The Waste Agency of Catalonia is responsible for the design of sectoral projects on waste and the provision of incentives for investment intended to reduce, recover and reuse waste. In 2014, the General Programme of Prevention and Management of Waste and Resources of Catalonia 2020 (PRECAT20) was established with this purpose. The 2018 report (Catalonian Waste Agency, 2018) recognized that a progressive and generalized implementation of more efficient systems of collection is needed to achieve these purposes. The regional council's responsibility is to determine the mechanisms necessary to guarantee the provision of municipal services, while the municipalities themselves provide selective collection, transport, recovery and disposal of municipal waste. Moreover, there is a special provision for the case of the Barcelona Metropolitan Area which includes the coordination of waste collection systems and the guarantee of the service in collaboration with the 36 municipalities that compose the area (Catalonian Waste Agency, 2018).

At this point, it is worth noting that urban waste accounts for a substantial portion of the waste generated in Spain, and especially in Catalonia. In 2016, households generated 16.8 % of the waste in the country, while the services and construction sectors generated 5.1 % and 27.8 %, respectively. The remaining waste was generated, in descending order, by the following sectors: industry; water provision, sanitation and waste management; and agriculture, livestock, forestry and fishing (INE, 2018). More remarkably, in Catalonia, in 2012, 35.6 % of the waste generated came from the municipal sector. Comprising a large part of the waste generated, it becomes relevant and necessary to understand what factors shape municipal waste management strategies and determine waste collection rates in cities. An empirical analysis of the many theoretically studied variables is yet to be done, especially in the context of rapidly urbanizing regions. Results that can be extrapolated to other regions of the world become useful in achieving a circular economy in cities.

The remainder of this paper is structured as follows. Section 2 provides a review of the relevant literature on the different aspects of SMSWC. The econometric model and the methodology are presented in Section 3. The materials, including the data and the theoretical expectations, are described in Section 4. The empirical results are depicted in Section 5 and discussed in Section 6. Conclusions and implications of the paper are presented in Section 7.

## 2. Literature review

Trying to provide useful information to policymakers on the socioeconomic and demographic factors influencing waste management in cities, various researchers have analysed waste separation behaviours and urban waste management in the past decades. Back in 1976, Reid et al. found a positive relation between the proximity of newspaper recycling containers to the places where common activities are carried out and the amount of newspapers collected for recycling. This highlights the importance of policy decisions in urban management and its effect on disposal behaviour. As the cities, their population and the waste problem grew, so did the amount of studies on the topic of waste management, especially since the beginning of the 20th century. An exhaustive literature review on social factors influencing household waste separation can be found in Knickmeyer (2020). A key conclusion of this study is the presence of a consensus on the importance of educational programs and communication to build a recycling culture. Similar to Reid et al. (1976), the author concludes that providing smart solutions to sort waste is the best way to ensure the participation of households, especially in high-density areas. Moreover, she demonstrates that the social behaviour on waste sorting varies greatly between urban areas. This variability feature is supported by our preliminary analysis of the heterogenous Catalonian SMSWC pattern shown in Fig. 1.

As discussed in the introduction, the role of governance highly matters when determining waste management strategies in cities. Vallero (2019) studied the governmental approaches of waste management that increase the strength and soundness of governmental actions. As he explains, waste management is the most important service a city can provide, and the local government is the only one with the ability to provide it fully. Waste management is a good indicator of how well the city can manage other services, such as health, transportation, and education. In this respect, if our study can prove useful to policymakers to delineate an effective waste management scheme, the results can have positive sprawling effects within cities' governance. Vallero also concludes that communication between local jurisdictions and stakeholders from the private and the public sector is key to secure an effective waste governance. In this context and focusing on a big metropolis, Batra et al. (2022) recently studied the waste collection and processing practices implemented by the Delhi authorities. Although only qualitatively, their review proves useful in emphasizing the need for collaboration between the governmental authorities, the private sector, and citizens to make improvements to the current waste urban waste management scenario. An analysis of the (lack of) governance in cities in Bangladesh corroborates the importance of this collaboration (Bhuiyan, 2010). The latter study also reminds us that in absence of strong governance, community based waste management initiatives function as replacement. Our results can be useful for this aspect of waste management governance, as they can shape how this public-private-citizens collaboration is devised. Although our analysis does not include waste management costs, it can provide useful information on the cities and households' characteristics to make a sensible assessment of the cost minimization and collection maximization strategies. When optimizing urban waste collection strategies, policymakers should take into account market dynamics, transaction costs, and service quality (Bel et al., 2010). In this sense, our study can provide useful information on the cities and households' characteristics to make a sensible assessment of the cost minimization and collection maximization strategies.

Because the strength of this study lies in its methodology, a review of previous techniques and models is appropriate. A common technique in the domain of waste management is Contingent Valuation (CV), which can be used to understand how citizens respond to different waste management options. Bartelings and Sterner (1999) conducted a CV survey to determine the willingness to pay of households for waste management solutions. Laboratory-based psychological studies have also been used to measure the participants' intentions to recycle under controlled conditions. Grazzini et al. (2018) conducted such an experiment and concluded that people have a higher propensity to adopt recycling actions when they know exactly how to do it. Similarly, Tonglet et al. (2004) made use of the Theory of Planned Behaviour, a cognitive psychological model, to understand the determinants of recycling behaviour. Some authors, such as Duggal et al. (1991) and Hage et al. (2009), have constructed consumer behavioural models to represent the payoff maximization of households when allocating leisure time on recycling efforts and other activities. These models serve to support the incorporation of policy design variables into our empirical analysis, as they demonstrate how moral and legal norms influence the recycling efforts.

Descriptive analysis to ascertain a correlation between explanatory variables and the rate of sorted waste collected is also common in the literature (Valenzuela-Levi, 2019a). The most used technique to analyse the factors influencing waste sorting behaviours and MSW collection rates is regression modelling. Some authors take advantage of probit models (Saphores et al., 2006), while most implement multiple linear regressions (Bartelings & Sterner, 1999; Grazhdani, 2016; Mateu-Sbert et al., 2013; Tonglet et al., 2004). Additionally, some authors have considered the issue of spatial association between political units when conduction regression analysis (Hage et al., 2018). The relevance of the spatial clustering present in our case study is discussed in in the recommendations. The observation units of this study are political units,

namely municipalities. The use of administrative divisions, such as municipalities and counties, has been repeatedly used as observation units (Callan & Thomas, 1997; Duggal et al., 1991; Hage et al., 2018; Valenzuela-Levi, 2019b). Nevertheless, the use of household level data is also extensive (Afroz et al., 2011; Babaei et al., 2015; Grazhdani, 2016). One of the advantages of using political units is the possibility to include not only socioeconomic and demographic variables, but also geographic and policy design, which in our case is relevant as we want to study not only the actions of citizens, but also the local strategy of authorities and its implications. At this point, we find relevant clarifying the semantics associated with our object of study, as there seems to be confusion in previous literature of what the terms represent. Previous studies most commonly use recycling rate and sorted waste collection rate as the object of study, depending on the availability of data and the research question. Contrary to what some might think, not all the (sorted) waste that is collected is finally recycled. Yet, in some cases, the terms are interchanged loosely. In our case study, our unit of measure is the (sorted) waste collected. This is important considering we are focusing on the socioeconomic and demographic aspects that can affect the rate of collection. Citizens' behaviour affects the recycling rate only indirectly, while authorities can sway the waste processing operations.

Achieving a more efficient waste management in cities requires better technologies and urban planning strategies that line up the stakeholders' incentives. Analysing the determinants of urban waste collection becomes a requisite in this complicated process (Arbulú et al., 2015). The present study aims at providing quantitative and qualitative tools that allow to better assess possible urban planning improvements related to waste management. Previous studies have highlighted the importance of understanding waste policies to reduce the generation (and increase the sorting) of waste (Kinnaman & Fullerton, 2000). An example of this is the studies on the effect of disposal charges (bag unit pricing) in the waste generation and sorting behaviour of households (Jenkins et al., 2003; Park, 2018; Podolsky & Spiegel, 1998). Another example that uses a simple approach and accessible data can be found in Lavee and Khatib (2010). They made use of a standard OLS regression analysis to identify what municipalities in Israel are best to implement waste recycling programs. Their results can be used by local authorities to make economically sound decisions about urban waste planning. More recently, Agovino et al. (2017) compared the effectiveness of a legislative decree aimed at improving waste collection rates in the North, Central, and South Italy. Their results indicate that poor infrastructures and lack of citizen participation in politics can prevent the implementation of waste management policies. Our study builds on their basic assumptions, although it does not compare specific policy outcomes. More importantly, the present study improves the econometric analysis of previous studies by including socioeconomic and demographic variables that can function to better capture the differences between regions. This aspect allows local authorities to produce more precise assessments of waste management resources.

The main contribution of our study to the existent literature lies in the combination of a large dataset and a comprehensive panel data methodology. It is recognized that this approach is valuable for the analysis of the complex issue of urban waste management (Estay-Ossandon & Mena-Nieto, 2018). Cross sectional studies have been previously implemented for the purpose of analysing waste management and recycling behaviours (Gaeta et al., 2017; Hage & Söderholm, 2008; Park & Berry, 2013). Nevertheless, longitudinal data have been used more commonly to conduct regressions on waste generation, collection, and recycling analyses. Relevant examples of panel data use can be found in Johnstone and Labonne (2004), Starr and Nicolson (2015), and Valenzuela-Levi (2019b). Although useful, these studies present issues of data availability that prevent drawing robust conclusions and effectively control for policy changes across time. The work of Sidique et al. (2010) on Minnesota counties from 1996 to 2004 is perhaps, to this day, the most comprehensive panel data analysis at a local level on urban waste collection rates. The same way they did, the present study improves previous econometric analyses on urban waste collection by taking advantage of the robustness of panel data. Another advantage of our approach is the use of revealed collection data, which provides more realistic results compared to previous questionnaire-based studies. Additionally, the use of policy related variables, disregarded in some of the aforementioned studies, coupled with a long timeframe, strengthen the reliability of the present study. A deeper discussion of the previously studied variables, the rationale to include them in our analysis, and the contradictory evidence on their effect is provided in the Theoretical expectations section.

The review presented above provides an outlook of the previous studies related to urban waste governance and planning, to the many factors influencing the waste collection rates, and to the varied methods that have been implemented to study these. The present study exploits the findings of the above literature, and uses the best techniques considering the data availability, the characteristics of the variables, and the needs of the local authorities to plan effective waste management strategies.

## 3. Methodology

Panel data are the most powerful econometric methodology to study a given phenomenon over a large set of individual entities (in this case: the Catalonian municipalities) during a long timeframe (20 years). In particular, panel data models with fixed effects (FE) and random effects (RE) are used for the analysis. A pooled OLS (POLS) model has also been computed as a consistency check for the results, as recommended, for example, in Wooldridge (2015). However, the POLS results will not be presented in detail because the RE model is more flexible and more efficient than POLS, and the results have indeed found to be consistent.

We specify a model of the following form:

$$y_{it} = \beta_0 + \beta X_{it} + a_i + u_{it}, \tag{1}$$

where y is the dependent variable SMSWC, $i$ denotes each municipality, and $t$ denotes the time period. $\beta_0$ is the intercept, $\beta$ is the k × 1 matrix of coefficients, and X is the 1 × k vector of explanatory variables:

$$\begin{aligned} X_{it} =& TOURESTA_{it} + COAST_{it} + WOMEN_{it} + NOCHILD_{it} + log\,(PDEN_{it}) \\ &+ ELDER_{it} + EDUC_{it} + log\,(INCOME_{it}) + FOREIGN_{it} + UNEMP_{it} \\ &+ DDC_{it} + POLT_{it}. \end{aligned} \tag{2}$$

All these variables are defined in Table 1.

The unobserved heterogeneity (or fixed effect), denoted as $a_i$, captures all unobserved, time-invariant factors that affect the explained variable. Finally, $u_{it}$ is the idiosyncratic (or time-varying) error that represents unobserved factors that change over time and affect the explained variable.

The FE estimator is unbiased if one can assume that there is no endogeneity (Wooldridge, 2015). Nonetheless, an inconvenience of the FE estimator is that, because it allows for arbitrary correlation between the explanatory variables and $a_i$ in any time period, the explanatory variables that are constant over time for all $i$, COAST and NOCHILD, are automatically removed from the model by the FE transformation. The fixed (or within) transformation turns the model into:

$$\ddot{y}_{it} = \beta \ddot{X}_{it} + \ddot{u}_{it}, \tag{3}$$

where the overdots indicate that the variable has been time-demeaned, i.e., the within-municipality time average for each variable is subtracted from the observed values of the variables. As can be seen, the fixed effects estimator removes all time-constant variables. It is relevant to note that, because the FE estimator uses the time variation in the independent and dependent variables within each cross-sectional observation, it will only explain differences within municipalities.

On the other hand, if it is assumed, additionally to all the assump-

**Table 1**
Variables definition, source, available years and expected influence on SMSWC rate.

| Variable | Definition | Source (available years) | Expected influence on SMSWC rate |
|---|---|---|---|
| *Dependent variable* | | | |
| SMSWC | Kilograms of sorted waste over total MSW collected annually | DOC, 2021a (2000–2019) | |
| *Geographic variables* | | | |
| TOURESTA | Number of tourist establishments (hotels, camping, and rural) per square kilometre | Idescat, 2019 (2000, 2002–2019) | Ambiguous (negative for Catalonia) |
| COAST | Dummy for coastal municipalities. 1 if coastal and 0 if not | DOC, 2021b (2000–2019) | Positive |
| *Demographic variables* | | | |
| WOMEN | Women as a share of total population | INE, 2019 (2000–2019) | Ambiguous |
| NOCHILD | Percentage of nuclear families without children | Idescat, 2014a (2001) | Ambiguous |
| PDEN | Population density | Idescat, 2020a; DOC, 2021a (2000–2019) | Positive |
| ELDER | People above 64 years old as a share of total population | Idescat, 2021a (2000–2019) | Positive |
| *Socioeconomic variables* | | | |
| EDUC | Percentage of the population with at least a bachelor's degree | Idescat, 2014b (2001,2011) | Positive |
| INCOME | Average general tax base as a measure of net disposable income | Idescat, 2020d (2000–2018) | Ambiguous |
| FOREIGN | Foreigners as a share of total population | Idescat, 2020b (2000–2019) | Negative |
| UNEMP | Number of people who are unemployed as a share of the labour force (aged 15 to 64) | SEPE, 2020; Idescat, 2021a (2006–2019) | Positive |
| *Policy variable* | | | |
| DDC | Dummy of municipalities with door-to-door waste collection service. 1 if serviced and 0 if not | AMCRPP, 2020 (2000–2019) | Positive |
| *Political preferences* | | | |
| POLT | Votes to left-wing parties as share of total votes in the general elections* | Idescat, 2017 (2000, 2004, 2008, 2011–2016) | Positive |

* The political parties are classified in the following way: Socialists' Party of Catalonia, Initiative for Catalonia Greens, Republican Left of Catalonia, In Common We Can, and Republican Left of Catalonia–Catalonia Yes are considered left-wing parties; and Convergence and Union, People's Party, Democratic Convergence of Catalonia, and Citizens are considered right-wing parties.

tions of the FE model, that there is no correlation between $a_i$ and the explanatory variables (whether time-variant or not), we find ourselves with a RE model. The RE estimator is computed in a way that allows for explanatory variables that are constant over time, which is an advantage over the FE model. In this sense, including COAST and NOCHILD will not pose a problem, although it must be assumed that these are uncorrelated with $a_i$. To see this better, let us transform Eq. (1) to construct an adaptable RE model equation:

$$y_{it} - \theta\bar{y}_i = \beta_0(1-\theta) + \beta(X_{it} - \theta\bar{X}_i) + (v_{it} - \theta\bar{v}_i), \quad (4)$$

where $v_{it} = a_i + u_{it}$. The overbar denotes the time average of the variable, and θ is a parameter that measures the variance of $a_i$ relative to the variance of $u_{it}$. When θ is close to zero, $a_i$ is relatively unimportant and Eq. (4) is similar to a POLS model. When θ is close to one, $a_i$ becomes important and the equation is close to the FE model described in Eq. (3). Because the RE model interpolates between OLS and FE depending on how much of the unobserved effect it attributes to the error term, it allows to study differences both between and within individual locations.

Considering FE allows arbitrary correlation between $a_i$ and the $X_{it}$, as opposed to RE, the former seems to be a more reliable estimate. Also, as Wooldridge (2015) remarks, when large geographical observation units are used, the sample cannot be treated as a random sample from a large population. In this case, it is logical to think of each $a_i$ as a separate intercept to estimate for each cross-sectional unit, which is what the FE estimator does. Nonetheless, when the explanatory variable is time-invariant or has minimal within- unit variation, FE will not work properly, and RE is preferred.

In addition to these theoretical considerations, we conduct several tests to assess the validity of each regression and make the appropriate adjustments and considerations. A Breusch-Pagan Lagrange multiplier test is used to verify significant differences across municipalities, and to compare POLS with FE and RE. Additionally, an F-test for individual and time effects is employed based on the comparison of the FE and the POLS regressions. Following the literature, we formally test for statistically significant differences between FE and RE with the Hausman test. To test for serial correlation in the idiosyncratic error of the regressions, $u_{it}$, the Lagrange multiplier Breusch–Godfrey test is used. A Pesaran's CD test is implemented to help determine if there is cross-sectional dependence in the specified models. Finally, a Breusch-Pagan heteroskedasticity test is conducted.

Because imputed data is used for some variables, as further explained in the Data section, different models have been calculated to evaluate the validity of the results and their robustness with respect to the concrete imputation method chosen. We will briefly comment on this issue where relevant, and focus on the complete model defined by Eqs. (1) and (3), including all independent variables and using imputed data wherever necessary. Time-dummies were included in all the regressions and, to simplify the interpretation of the coefficients, logarithmic transformation was applied to the variables PDEN and INCOME.

## 4. Materials

### 4.1. Data

Catalonia, as of 2020, has 947 municipalities (Idescat, 2020c). For the analysis, the data of some municipalities were manipulated because of geopolitical reasons,[1] resulting in a longitudinal data set of 18.880 observations: 945 Catalonian municipalities from 2000 to 2019. The explanatory variables are classified into five categories: geographic, demographic, socioeconomic, policy related, and political preferences. A list of the variables, their description, their source, and the available years of their data can be found in Table 1. The expected influence of each independent variable on the SMSWC rate, based on previous considerations in the academic literature, is also included in Table 1, and

[1] The data for Medinyà was added to Sant Julià de Ramis, as the former was an independent municipality from 2015 to 2018, when it was reincorporated into the latter (Rodríguez, 2018); The data for La Canonja data was added Tarragona because the former was segregated from the latter in 2010 (La Información, 2010); Finally, the data for Tiurana data was deleted from the data set, as the municipality was founded in 2007 (CCMA, 2007).

**Table 2**
Summary statistics.

| Variable | N | Mean | St. dev. | Min | Pctl(25) | Pctl(75) | Max |
|---|---|---|---|---|---|---|---|
| SMSWC | 18,900 | 25.53 | 16.79 | 0.00 | 13.30 | 33.48 | 100.00 |
| TOURESTA | 18,900 | 0.20 | 0.48 | 0.00 | 0.01 | 0.20 | 9.12 |
| WOMEN | 18,900 | 48.39 | 2.65 | 23.19 | 47.28 | 50.03 | 71.94 |
| NOCHILD | 968 | 32.79 | 6.69 | 13.33 | 28.67 | 36.36 | 69.23 |
| NOCHILD.Prop | 18,900 | 32.82 | 6.75 | 13.33 | 28.65 | 36.40 | 69.23 |
| PDEN | 18,900 | 421.75 | 1552.00 | 0.69 | 12.33 | 168.20 | 21,364.00 |
| ELDER | 18,900 | 21.15 | 6.73 | 5.26 | 16.03 | 25.74 | 58.54 |
| EDUC | 1,399 | 11.62 | 5.52 | 0.90 | 7.99 | 14.13 | 46.32 |
| EDUC.Prop | 18,900 | 11.22 | 5.25 | 0.90 | 7.69 | 13.79 | 46.32 |
| INCOME | 18,900 | 16,099.00 | 5468.00 | 0.00 | 12,422.00 | 19,442.00 | 95,206.00 |
| FOREIGN | 18,900 | 8.32 | 6.59 | 0.00 | 3.54 | 11.20 | 51.85 |
| UNEMP | 13,077 | 7.19 | 3.49 | 0.00 | 4.62 | 9.38 | 28.81 |
| UNEMP.Itera | 18,900 | 6.92 | 3.33 | 0.00 | 4.54 | 8.94 | 32.84 |
| POLT | 18,900 | 47.14 | 13.61 | 6.76 | 36.86 | 58.23 | 92.86 |
| Dummies (yes: 1, no: 0) | | | | | | | |
| DDC | 18,900 | 0.088 | | | | | |
| COAST | 18,900 | 0.074 | | | | | |

will be detailed in the Theoretical expectations section below. Additionally, a summary of the variables' statistics is depicted in Table 2.

To construct the dependent variable, SMSWC, the following materials are considered sorted waste: organic, paper, glass, light packages (plastic, metal, non-metallic and compound packaging), electrical and electronic devices, cooking oil, textile, batteries, medicines, and other selective waste (small quantity of varied waste collected at recycling drop-off centres). The SMSWC rate is computed in units of kilograms of sorted waste over the total MSW collected annually. A box plot grouped by years, which also illustrates the increase from 9 % to 41 % of the average SMSWC rate in Catalonia from 2000 to 2019, is shown in Fig. 2.

Data of several independent variables are missing for different periods of time, either because of the nature of the variable or because their collection was sporadic. The variables for which only a year of data is missing were filled with the adjacent year's data. When more than a single year was missing, different types of imputation methods or filling mechanism were tested depending on the characteristics of the variables and the reason for the missing values: interpolation of the values; propagation of the closest valid observation, forward or backward depending on the available years; and iterative imputation, a tool inspired by the R MICE (Multivariate Imputation by Chained Equations) algorithm, which uses available data to model the feature with missing values and uses the estimate to impute them (Pedregosa et al., 2011). An assessment of the imputation results of the data of three variables (EDUC, UNEMP, and NOCHILD) with substantial missing observations is carried out through a graphical diagnosis, in accordance with Bondarenko and Raghunathan (2016) and Nguyen et al. (2017). Only the most robust method has been withheld for each variable. In particular, for NOCHILD and EDUC, propagation turns out to be the preferred method, whereas for UNEMP the iterative method is superior.

### 4.2. Theoretical expectations

We will now proceed, for each independent variable, to detail the theoretical expectations which were summarized in Table 1 above. All independent variables were selected either because their influence was

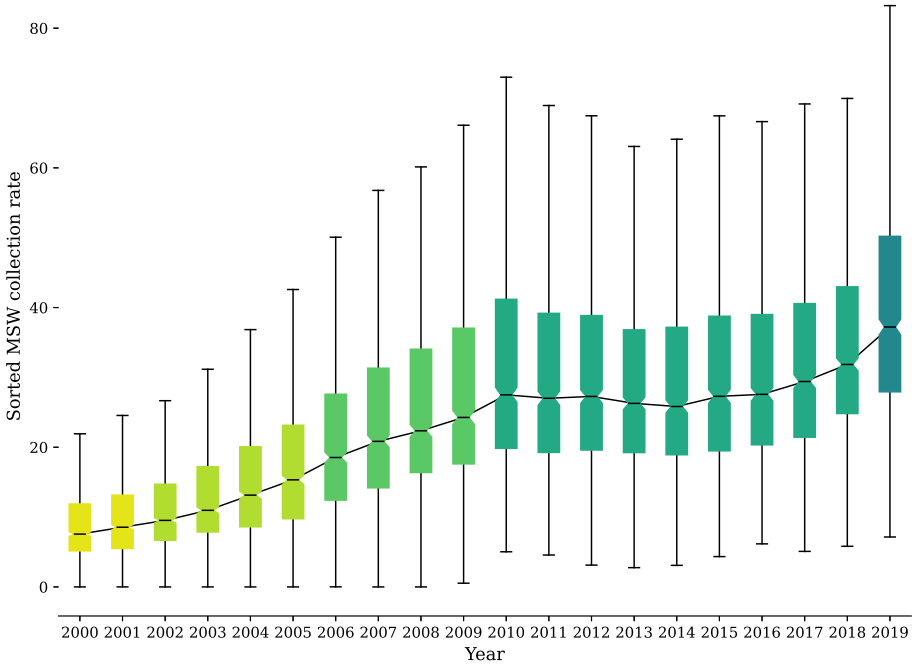


**Fig. 2.** Average selective MSW collection rate in Catalonia.
(Source: DOC (2021a).)

previously identified in the relevant literature, or by theoretical reasoning. As explained in the introduction, the working hypothesis consists in confirming the significance and effect (positive or negative) of those variables on which there exists agreement in the academic literature. When no previous consensus exists, our main concern lies in determining the significance and impact (positive or negative) of the variable.

The first geographic independent variable selected is Tourist Accommodation Establishments (TOURESTA). The impact of tourism on the rate of SMSWC has been previously analysed by Mateu-Sbert et al. (2013), who concluded that a resident in Menorca Island selectively collects on average 47.3 % more than a tourist. Arbulú et al. (2015) also studied the role of tourism in urban waste collection rates with the aid of the Environmental Kuznets Curve. They mention that, although tourism is intensive in urban waste generation, it could be a catalyser for better waste governance because tourism destinations image is sensitive to environmental damage. Moreover, their results confirm the importance of including the role of tourism in urban waste analyses. They conclude that tourism increases MSW generation up to a turning point where the trend reverts. Although the TOURESTA variable we include is not measured by actual tourist population, it is closely related. For this particular variable, because of the high intensity of tourism in Catalonia, we expect it to lie in the upper part of Arbulú et al.'s (2015) Kuznets model, and hence to contribute negatively to the SMSWC rate.

As a second geographical variable, the binary variable COAST has been included. In their study, Milfont et al. (2014) suggest that people who live closer to the coast express a greater belief that climate change is real. Therefore, it is expected that people living near the coast show a higher propensity to sort waste, and that the variable COAST has a positive influence on the SMSWC rates.

We have considered four demographic variables. The first one is WOMEN, as it has been previously observed that women are more willing to pay for environmentally sound waste management than men (Bartelings & Sterner, 1999). Nevertheless, Hage et al. (2009) determined that gender does not affect recycling behaviour much. Thus, our intent is to confirm if there is evidence of women playing a role in the SMSWC rate. The second demographic variable is NOCHILD, for which data is available only for the year 2001. These data have been propagated across the entire period, and the variable has been treated as a time-invariant regressor. This approach limits the quality of the variable, as the population structure can vary greatly in twenty years. Nevertheless, this approach is expected to be sufficient to verify whether the differences between municipalities are significant in the specified model. Johnstone and Labonne (2004) explain that the number of children in the household is important because consumption expenditure patterns for households with children are different, which can result in different patterns of MSW generation. They conclude that children have a negative influence on waste generation. Inversely, Knickmeyer (2020) notes that children can have a positive influence on the family's behaviour, as they are usually educated on environmental protection at school. It is thus hoped that the analysis will corroborate one of these hypotheses or conclude that there is no significant effect in the case of Catalonia.

PDEN, the third demographic variable, was chosen because population density has been found to have a positive effect on the quantity of waste collected (Bartelings & Sterner, 1999). It has also been noted that investments in recycling infrastructure and education are more cost-effective in densely populated areas (Grazhdani, 2016), which could induce a higher sorted waste collection rate. Finally, Berglund and Söderholm (2003) show, for paper waste, that a high population density generally implies higher recovery rates. Therefore, we anticipate that more densely populated municipalities will have a higher SMSWC rate. Lastly, in the demographic category, elderly people (ELDER) was selected as an age-effect variable. Although it is often believed that the young population tends to be more environmentally aware, Sidique et al. (2010) and Hage et al. (2009) concluded that age has a positive effect on the SMSWC rate because people who are older usually have more time to spend on waste sorting activities. Thus, ELDER is expected to be positively correlated with SMSWC.

Let us now turn to socioeconomic variables. The data of EDUC, the first socioeconomic variable, are available for 2001 and 2011 (in the latter only for 465 municipalities). Because of its relevance, it was preferred to conduct an imputation of the data rather than leaving the variable out of the model. The rationale to include education as an independent variable is evident and well documented. Education is expected to be positively correlated with the rate of SMSWC as more educated people are expected to be more aware of environmental issues, which encourages them to selectively dispose of waste (Grazhdani, 2016; Sidique et al., 2010). INCOME, measured using the average general tax base, is the second socioeconomic variable. The theoretical expectations with respect to this variable are ambiguous. On the one hand, people with higher income generally consume more and therefore tend to generate greater amounts of waste (Grazhdani, 2016). This behaviour inevitably increases the probability of non-selectively disposal of waste. Also, the opportunity cost for the high-income households is greater because waste sorting is a time-consuming activity. On the other hand, Hage and Söderholm (2008) note that, empirically, waste sorting efforts have a tendency to be positively correlated with income. The third socioeconomic variable, FOREIGN, is relevant for this study because cultural norm differences can affect the waste sorting behaviour and other environmental protection practices. The results of Johnson et al. (2004) indicate that, irrespective of socioeconomic aspects, environmental belief and activism vary by ethnicity. Also, according to Hage et al. (2018), newly arrived migrants are usually not familiar with local recycling and waste collection regulations, which can reduce the sorted waste collection rate. Nonetheless, it can be inferred that, as time goes by, immigrants become familiar with the regulations and the social norms, and this negative effect is alleviated over time. Unemployment rate (UNEMP) is the last socioeconomic variable selected for our analysis. Iterative imputation has been used to fill the missing values of the 2000–2005 period. The rationale to include unemployment in the model is similar to that of ELDER: people who are unemployed usually have more time to spend on waste sorting activities (Hage et al., 2018).

The fourth independent variable category included in the model consists of policy variables. This category consists of a single variable, namely the door-to-door collection variable (DDC), which is also the second dummy variable of our model. Municipalities in which at least 50 % of the population is served with door-to-door collection were considered as having a DDC service. This service generally accomplishes a higher level of selective waste collection than street containers collection (fixed drop-off points located along sidewalks) because the distance to be covered to deposit the waste is kept to a minimum (Johnstone & Labonne, 2004; Ventosa et al., 2013). Thus, it is expected that municipalities with DDC service will perform better and score higher on the SMSWC rate.

Finally, POLT, the last independent variable of the analysis addresses political preference. Since the general elections take place every four years, it can be considered that the results of the elections are representative for the entire four-years term. Thus, the values have been propagated forward. The political preference can be an important determinant of the SMSWC rate, and it might explain differences between municipalities. Specifically, similarly to what Xiao and Buhrmann (2019) suggest, we expect to find that those municipalities in which the majority of votes are for left-leaning political parties tend to have a higher SMSWC rate.

Additionally, we want to verify whether an active waste selective collection policy can dominate all other (geographic, demographic, socioeconomic and political) variables. The underlying idea is that an active policy is the only variable on which governments can have a direct, and controllable impact, and it is thus the easiest to act upon in order to achieve desired SMSWC rates. These hypotheses are summarized in Table 3 below. Note that H1 and H2 are composite hypotheses;

**Table 3**
Working hypotheses: summary.

| Hypothesis (description) | Corresponding variables |
|---|---|
| H1: Confirm theoretical expectation of impact (positive or negative) based on literature consensus | Positive: COAST; PDEN; ELDER; EDUC; UNEMP; DDC; POLT<br>Negative: FOREIGN |
| H1.1: Confirm local expectation based on literature models | Negative: TOURESTA |
| H2: Variable is significant. Impact (positive or negative) to be determined | WOMEN; NOCHILD; INCOME |
| H3: Policy variables can dominate all other categories | DDC |

in other words, they could be rejected for some variable and confirmed for some other.

## 5. Results

The main results obtained through the RE and FE regressions are presented in Table 4. To obtain an idea of how well this model fits the observed data, the FE prediction and its residuals are shown in Fig. 3.

Before discussing these results in detail, we make a few observations of methodological consistency. First, note that the Lagrange Multiplier test for the POLS rejects the null hypothesis of not having significant time and individual effects, thus establishing the preference of FE or RE models over POLS. Additionally, the F-test comparing the POLS to the FE model verifies the existence of individual differences between municipalities. The null hypothesis of no correlation between the idiosyncratic errors, $u_i$, and the regressors of the model is rejected by the Hausman test. Thus, from a purely methodological point of view, the RE model is in principle inconsistent. Nevertheless, as explained in the Methodology section, because FE cannot explain the effect of time-invariant variables on the explained variable, RE is useful to understand how COAST and NOCHILD possibly affect the explained variable. Furthermore, as remarked in Clark and Linzer (2015), in practice, the violation by the RE model of the assumption that the regressor and the individual effects are uncorrelated seems insufficient reason to rule out this model. The Breusch–Godfrey test indicates the presence of serial correlation in the idiosyncratic error in all five models. Moreover, by means of the Pesaran's CD test, the null hypothesis stating that the residuals do not present cross-sectional correlation is rejected. Finally, the Breusch-Pagan test indicates the presence of heteroskedasticity in the FE model. Hence, due to the presence of autocorrelation, cross-sectional dependence, and heteroskedasticity in the models, we compute fixed effects SCC (spatial correlation consistent) estimates using the Driscoll and Kraay's robust covariance matrix estimators. This method was preferred to the Heteroscedasticity-Consistent Covariance Matrix Estimation (HAC) as the latter does not handle the problem of cross-sectional dependence (Driscoll & Kraay, 1998).

**Table 4**
Regression results for sorted MSW collection rate in 945 Catalonian municipalities.

| | Dependent variable: SMSWC | | Impact on hypotheses (see Table 3) |
|---|---|---|---|
| | RE | FE with SCC | |
| TOURESTA | −0.015 | −0.141 | H1.1 confirmed |
| | (0.298) | (0.255) | |
| COAST | −2.895** | | H1 rejected |
| | (1.162) | | |
| WOMEN | 0.075 | 0.086* | H2: weak significance, positive |
| | (0.047) | (0.052) | |
| NOCHILD. Prop | −0.240*** | | H2: strong significance; negative |
| | (0.042) | | |
| log(PDEN) | −0.292* | −6.965*** | H1 rejected |
| | (0.172) | (0.916) | |
| ELDER | 0.048* | −0.006 | H1 confirmed |
| | (0.028) | (0.053) | |
| EDUC.Prop. | 0.062** | 0.092(**) | H2: significant, positive |
| | (0.031) | (0.124) | |
| log(INCOME) | 0.492** | 0.227* | H2: significant, positive |
| | (0.196) | (0.134) | |
| FOREIGN | 0.057** | 0.112*** | H1 rejected: strongly positive |
| | (0.023) | (0.027) | |
| UNEMP.Itera | −0.060 | −0.081*(*) | H1 rejected |
| | (0.039) | (0.045) | |
| DDC | 26.968*** | 26.735*** | H1 confirmed; strongly positive H3 confirmed |
| | (0.339) | (1.125) | |
| POLT | 0.047*** | 0.043(***) | H1 confirmed |
| | (0.014) | (0.029) | |
| Constant | 7.046** | | |
| | (3.330) | | |
| R2 | 0.589 | 0.600 | |
| Adjusted $R^2$ | 0.589 | 0.578 | |
| F-statistic | 27,073.070*** | 926.671*** | |

Note: Time dummies were included in all regressions. The FE model R2 and F -Statistic are obtained before the SCC transformation. Significance levels between brackets are also from the basic FE Model and have been reduced due to the SCC transformation, which in some cases could be a spurious effect, as discussed in the main text.
Significance levels: *p < 0.1; **p < 0.05; ***p < 0.01.

Both models show an F-statistic with $p < 0.001$, indicating that there is a linear relationship between all the explanatory variables considered together and the SMSWC rate. In other words, there is at least one independent variable significantly related to the explained variable. Therefore, a linear regression model provides a significantly better fit than a model with no explanatory variables. The $R^2$, interpreted as the percentage of the variation in SMSWC across time that is explained by the model, lies between 0.50 and 0.60. Note that the addition of year-dummies can lead to an overestimation of the $R^2$, since each year's coefficient explains a certain amount of variation in the explained variable. Nevertheless, this measure provides an idea of how well the models fit the data.

With respect to the RE results, the following features are observed. TOURESTA and WOMEN are not significant at the 10 % level. COAST is significant and has a negative relation with the explained variable. NOCHILD is significant and negatively related to SMSWC. As for log (PDEN), this is significant at a ten percent level, but its effect is relatively small: a one percent increase in the population density decreases the rate of sorted MSW collected by 0.003 units, which translates to a decrease of 0.003 percentage points, as this is the unit of measure of the explained variable. EDUC is statistically significant and positively related to the explained variable. The magnitude of its effect is different depending on the imputed method considered. As mentioned above, propagation is preferred, for which a one percentage point increase in EDUC increases SMSWC by 0.062 percentage points. The use of a different sample size can probably influence the concrete estimation, but the qualitative conclusion of a significant and positive effect of EDUC on the dependent variable is robust. Log(INCOME) is significant and positively related to SMSWC: a one percent increase in the average general tax base increases the rate of sorted MSW collected by 0.0049 percentage points. FOREIGN is statistically significant at a five percent level and is positively related to the dependent variable. UNEMP is negatively related to SMSWC in all models, but not significant at a 10 % level. Finally, DDC and POLT are positively related to the explained variable, and they are statistically significant at a 1 % level. DDC produces a relatively large effect: municipalities provisioned with door- to-door sorted waste collection have, on average, a sorted MSW collection rate 0.27 percentage points higher than those without DDC.

The results for FE are described compared to the Driscoll and Kraay's estimates, which improve their robustness. WOMEN is statistically significant at a ten percent level, and it has a positive effect of around 0.09 percentage points in SMSWC for every percentage point increase in the share of women population. Population density is significant, and it affects the rate of sorted MSW collection negatively, with an approximate effect of 0.07 percentage points. The significance of the EDUC

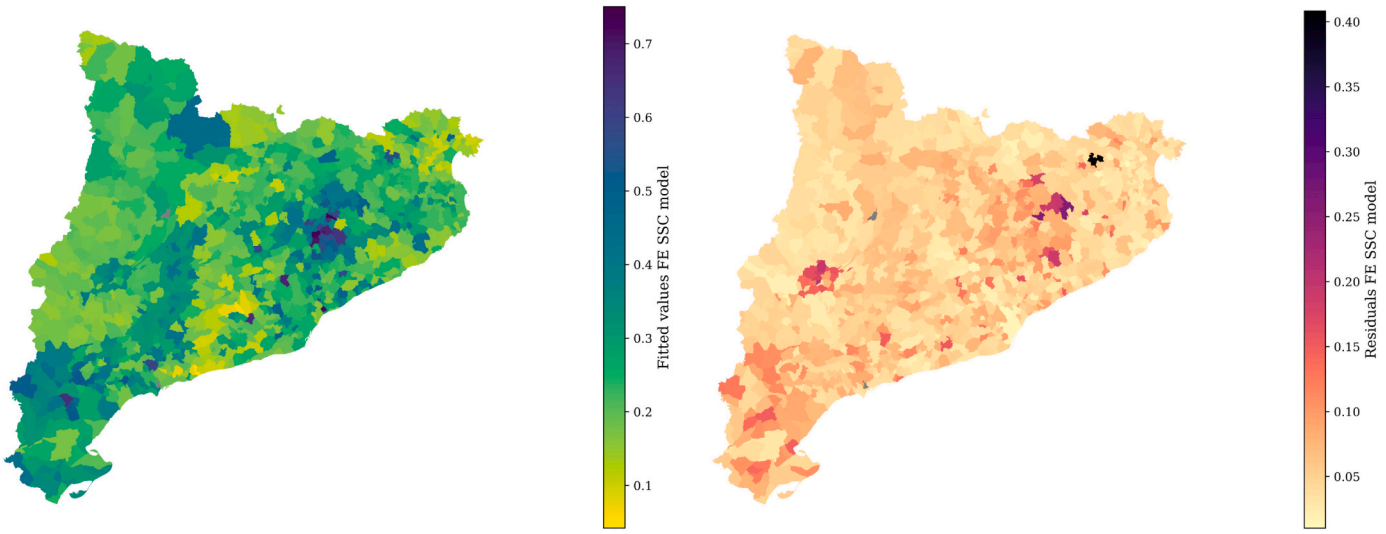


**Fig. 3.** Modelled average selective MSWCR (2000–2019). Left: prediction from the Econometric model of Eq. (1) with fixed effects (FE) using the regression coefficients of Table 3. Right: residuals with respect to the observed average values of Fig. 1.

variable in its propagated form is wiped out by the Driscoll-Kraay transformation. INCOME has a slightly significant effect and is positively related to the dependent variable. As for FOREIGN, it is highly significantly and positively related to the explained variable. Its relatively high coefficient is also noteworthy: a percentage point increase in the rate of foreign population increases the SMSWC rate by 0.11 percentage points. UNEMP is significant only at a ten percent level, but its negative effect is consistent with that of the RE results. The policy variable DDC is highly significant and shows a strong positive relation to SMSWC, with a coefficient close to the one found in the RE regression. Finally, the rate of left-wing votes in general elections is positively related to the explained variable, but it is not significant when implementing the Driscoll and Kraay's standard errors estimates.

For an easy visual interpretation of these results, the regression coefficients and their standard errors are represented in Fig. 4. This figure should be interpreted with some care, because the units of the variables can be absolute numbers, logarithms or percentages, as described above. However, the strong impact of DDC (Door-to-Door Collection), as well as the negative influence of COAST, is immediately clear from the left figure. The rescaled figure on the right illustrates the consistency between the FE and RE models, while also allowing to appreciate the positive or negative influence of the variables included in the study.

## 6. Discussion

The results described above shed light on which of our predictions are corroborated empirically, and how the specified theoretical model considerations manifest in this large-scale study. For most variables, there is a good qualitative agreement between the results produced by the RE and FE models, and the estimated effects are in most cases of the same order of magnitude. In cases where the methods show different results, the FE model is the safest model to draw conclusions from, since RE estimates require that the fixed effect is not correlated to the independent variables. Let us briefly discuss the variables in turn, and compare the estimations with the theoretical expectations formulated in the Materials section. The following discussion is also summarized in Table 4. Particular emphasis will be placed on the cases where the theoretical prediction based on previous consensus in the literature (H1 in Table 3) is rejected. In those cases, we will argue whether we expect the cause of this rejection to be the local characteristics of Catalonia or

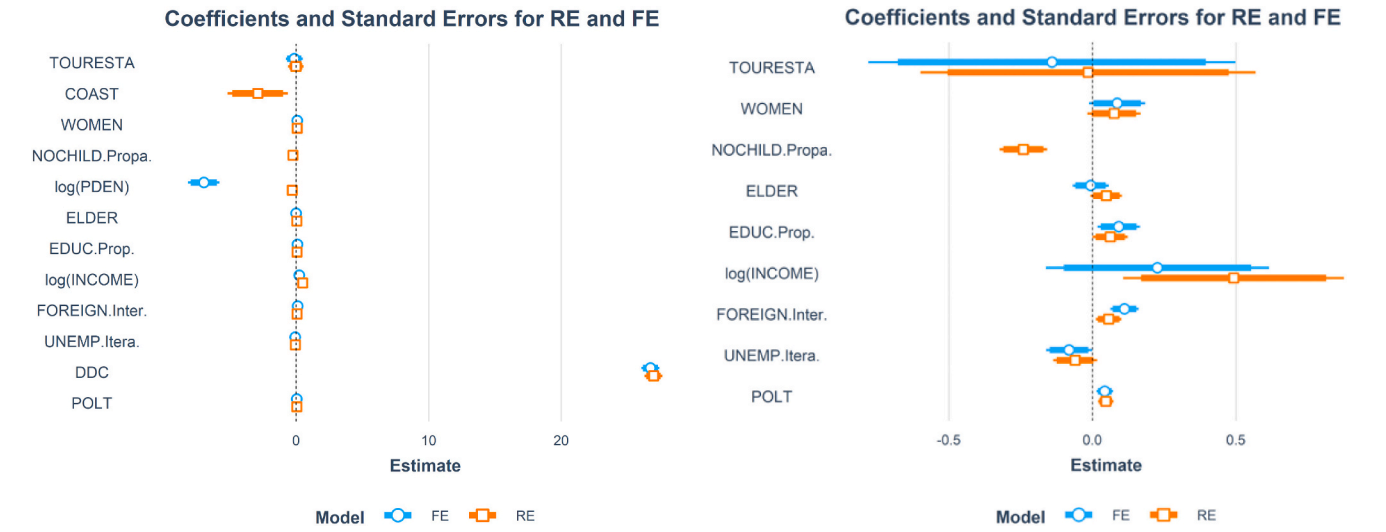


**Fig. 4.** Regression coefficients and standard errors for random effects (RE) and fixed effects (FE) model of all independent variables (left) and detail without PDEN, COAST and DDC (right).

the more generic factors which could be extrapolated to other regions.

Opposite to previous literature, the present study indicates that municipalities on the shore show a lower rate of sorted MSW collection than the inland municipalities. This could be explained by the fact that, as coastal areas are more touristic, the rate of sorted waste collected is smaller. Indeed, as can be observed in the regressions results, the variable which measures tourism, although not significant, is negatively related to SMSWC. This is in line with the theoretical model explained above, namely that tourism increases the concern of local residents for a clean environment, whereas tourists themselves tend to generate more waste. As more generation is correlated to less effort dedicated to selective sorting, intense tourism is likely to negatively affect the SMSWC rate. In this sense, the rejection of the theoretical expectation (H1) for the COAST variable is probably due to the local configuration of Catalonia, which incorporates a highly touristic coastal area. But since such a configuration is far from unique to Catalonia, we therefore expect similar results for other coastal touristic areas.

FE and RE estimates provide similar, small, positive, and barely significant coefficients for the rate of women population. This result coincides with the expectations formulated in the Materials section. With respect to families having children at home, these affect the sorted waste collection rate positively. This can be thanks to the environmental education taught at schools, as Knickmeyer (2020) suggested, although more causes could play a part. Indisputably, and contrary to the conclusions of previous studies in other regions, population density has a negative effect on the rate of SMSWC in Catalonian municipalities, thus rejecting H1 for this variable. A 0.07 percentage points decrease (per one percent increase in population density) could be considered a relatively small effect. However, population density can vary substantially across time. As an example, the population density of Barcelona increased 8 % from 2000 to 2019, thus leading to a substantial, negative contribution to the SMSWC rate. Future research is needed to further clarify the role of population density.

The average general tax base, used as a measurement of average income, is positively correlated with the rate of sorted waste collected, as Hage and Söderholm (2008) estimated, and has a rather substantial effect. Note that the 2009 financial crisis seems to have increased this effect. A possible explanation is that low-income municipalities, affected by the crisis, could not allocate as much money into recycling solutions as before, leading to a magnification of the income effect. As expected, the percentage of the population with higher education has a positive effect on the sorted MSW collection rate, although its significance at a 5 % level disappears after applying the Driscoll-Kraay SCC transformation in the FE model.

A surprising result is the effect of foreign population. Contrarily to what previous studies indicate, foreign population has a positive, and in fact relatively large coefficient of 0.11, thus strongly rejecting H1 for this variable. A better understanding of this result requires further research, but we speculate that the implementation of different immigrant integration programs in the municipalities could have played a role. Another unexpected result, though less significant and less outspoken, is the negative effect of unemployment rate on the rate of SMSWC.

Door-to-door collection is by far the variable with the largest effect on the explained variable, and it is definitely significant. This result not only corroborates previous studies, but it also gives support to the implementation of door-to-door collection schemes in more municipalities. More generally, it supports hypothesis H3, namely that active waste collection policies can overcome the limiting effect of other independent (geographic, demographic or socioeconomic) variables and achieve a satisfactory SMSWC rate.

Finally, the percentage of votes to left-wing parties has a positive effect on sorted waste collection rates in Catalonian municipalities, as concluded by previous authors. Yet, its significance in the FE model is not robust to the Driscoll-Kraay transformation, as it happens with education. However, it is plausible that this SCC transformation removes the significance of the POLT coefficient because it identifies serial correlation produced by the data propagation across the legislature periods. Since this coefficient is significant at a 1 % level before applying the SCC transformation, as well as in the RE model, we tentatively consider the effect of this variable to be significant.

As discussed in the Introduction, there are good reasons to believe that these results are not limited to the case of Catalonia, but can be extrapolated to much of Southern Europe, and even to other regions in the world with a similar socioeconomic structure, now or in the near future. In that sense, the comprehensiveness of the methodology in combination with the vast range of data analysed confers a large amount of trust in the results obtained. It is worth stressing that many of the statements found in the literature build on theoretical arguments or small-scale studies, thus making this large-scale confirmation robust and valuable. Also, a few of the results were surprising and even contradicted the existing literature.

An obvious limitation of the methodology is that although a powerful way to quantify various effects, it does not contribute to their interpretation. A cautious attempt has been made to suggest possible interpretations, especially when these were surprising. Yet, future research is needed to achieve a more detailed understanding of the reasons behind the effect of factors on the sorted waste collection rate in cities. In particular, for variables for which our results contradicted previous statements in the literature (population density, unemployment, foreign population), it is recommended to perform a meta-analysis similar to Miafodzyeva and Brandt (2013) or Morris et al. (2013). This would be useful to verify whether the effect of the variables depend on local peculiarities, or whether a Kuznets-like behaviour applies to them, similar to the one described by Arbulú et al. (2015) for the relation between tourism and waste generation.

Another limitation is that waste management related costs were not included in the present study. In this sense, while the recommendation of increasing Door-to-Door Collection is obvious based on the strong impact demonstrated above, a cost-benefit analysis (CBA) is necessary before leading to concrete policy recommendations. Although a CBA depends strongly on local structures and political agendas, our results prove useful to delineate possible alternatives to current practices. A related and more general issue is that waste collection, although crucial, is only one step in the entire ecological cycle of waste management. The actual recycling and reusing of waste materials are other components in this cycle. Undoubtedly, these components require further investment efforts, thus competing with strict waste collection strategies such as DDC. In this context, stated preferences techniques and other behavioural economics tools can be helpful to complement our findings regarding socioeconomic and demographic variables. Such analyses could provide information on how households reason when considering waste management options. Combined with our results, these analyses can help optimize government policy and household action, while taking budget constraints into account. We will come back to these limitations, as well as to some tentative recommendations, in the Conclusions below.

## 7. Conclusions

Using longitudinal data of solid waste in Catalonian municipalities, this study aimed at determining and analysing geographic, demographic, socioeconomic, policy-related, and political preference variables affect the management of waste in cities and their surrounding areas. The paper implemented a careful methodological evaluation on a large set of data (20 years across 945 municipalities with a total current population well over 7 million). The present case study is argued to be representative for much of Southern Europe, as well as a showcase for many other regions in the world where ecological considerations are likely to play an increasing role in the future. It was shown that the proximity to the coast, the population density, the unemployment rate, and the absence of children in the household contribute negatively to the rate of sorted MSW collection. Vice versa, the rate of women

population, the average income, the percentage of foreigners, the door-to-door collection services, and the rate of votes to left-wing parties are positively related to the rate of sorted MSW collection. Additionally, it was found that the effects of the rate of elderly population and of the number of tourist establishments per square kilometre do not affect the rate of sorted MSW collection significantly. Most of these results are in line with previous findings in the literature. Thereby, the present study serves to firmly establish theoretical considerations and tentative conclusions obtained from previous, smaller-scale studies. Some of the obtained results, on the other hand, and in particular the negative influence of the proximity to the coast and of population density, contradict previous studies. With respect to the coastal factor, we speculate that there is a trade-off due to the high impact of tourism in the Catalonian coast, and expect this is the case for other touristic coast regions. As for population density, while it can in principle lead to more optimal waste collection, it seems there is a limit to its effect, which certainly deserves further study to be better understood, and possibly acted upon by urban planning strategies.

In terms of management, the question is how local authorities can act over these factors to implement more efficient local waste management policies, in Catalonia and elsewhere. The conclusion about the implementation of door-to-door collection services is clear and explicit. Its effect on sorted waste collection rates is substantial and highly significant. Luckily, it is also a factor that can be acted upon directly by local governments. Although it is recommend to supplement this finding with a CBA, our results should serve as a source of motivation and optimism for urban planners to act on a policy that was found to be far more relevant than any of the geographic, socioeconomic and demographic variables. In other words: urban policy can make a crucial impact on waste collection rates in cities. Studies on the optimization of the waste collection points location can be a valuable complementary analysis to our study. A concrete example is the study by Alvarez et al. (2009) using Geographic Information Systems. They provide practical information for the implementation of urban planning strategies, and a possibly more cost-effective alternative to door-to-door collection.

Apart from the door-to-door collection variable, other variables have an important explanatory power, but do not allow direct policy intervention. Nevertheless, indirect action can have long-term benefits. In particular, extrapolation from the concrete analysed variables allows us to make the following suggestions. The first one is the positive effect of education on recycling behaviour, which is well known and needs no further explanation. The second one is more innovative. The population share of foreigners was found to have a positive impact on recycling behaviour in our study. We therefore venture to speculate that internationalization, not only in a strict demographic sense, but in a more general sense of the open-mindedness promotion and global solidarity, can also have a positive long-term ecological effect. Finally, the strong negative influence of population density suggests giving attention to changes of population density within municipalities. Furthermore, and more importantly, recycling policies should be differentiated based on the local population density.

Despite the relevant contributions of this study to the understanding of the factors influencing the rate of sorted waste collection in cities, there are limitations to this analysis that should be considered in future research. If complete data for the analysed period can be collected, the quality of the analysis would improve. Moreover, if surveys on willingness to recycle can be carried out effectively, qualitative data can shed light on households' perceptions and attitudes towards sorted waste collection schemes. This could not only corroborate relationships between socioeconomic and demographic characteristics of cities and the rate of SMSWC, it would also help establishing detailed and differentiated local actions. In this sense, the paper also highlights the importance of collecting local data to assess the implementation of more efficient regulations. Local data can allow policymakers to employ the framework and methodology presented here to guide their waste policies and achieve sustainable development targets. Additionally, promoting waste management data collection in cities would generate a positive, constant feedback loop of the impact and efficiency of the different policy measures.

In light of the previous considerations, our first recommendation to local authorities is to systematically collect and disclose waste management data. Not only tonnage of sorted waste collected, also collection points location, collection frequency, jurisdictional information etc., can prove useful when determining urban waste management strategies. These data are also an essential prerequisite for our second recommendation, namely carrying out detailed studies of the many factors influencing the success of existing waste management strategies. Such studies can detect exceptional cases in neighbourhoods, cities, or regions, and allow scaling down from the large-scale quantitative results obtained here to more local details of why and how. Third, if new policies are to be implemented in a city, qualitative analyses considering the costs-benefits and the potential response of dwellers must be conducted to maximize the positive results of the policies, and to prevent pitfalls. The combination of these factors, together with continued efforts at public consciousness and education, should also allow public entities at different (local, regional and national) levels of government to better synchronize their efforts, and help reach the objectives of the European green agenda.

Finally, a concrete recommendation for further research would be to account for a potential spatial dependence. By implementing measures of spatial autocorrelation, new findings on the existence of clusters and the influence of neighbouring municipalities can be presented.

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## CRediT authorship contribution statement

**L. Ignacio Saldivia-Gonzatti:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Validation, Writing – original draft. **Gil Jannes:** Conceptualization, Formal analysis, Project administration, Supervision, Visualization, Validation, Writing – review & editing. **Jesús Barreal:** Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Visualization, Validation.

## Declaration of competing interest

The authors have no conflicts of interest to declare.

## Data availability

The paper defines and describes the research data sources.

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