Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Impact of COVID-19 lockdown measures on waste production behavior in Lisbon

Pedro Sarmento*, Marcel Motta, Ian J. Scott, Flávio L. Pinheiro, Miguel de Castro Neto

NOVA Information Management School (NOVA IMS), Universidade Nova de Lisboa, Campus de Campolide, 1070-312 Lisboa, Portugal

ARTICLE INFO

Keywords:
Mixed waste
Recycled waste
Waste collection circuits
Tourism
Residential
COVID-19

ABSTRACT

The recent restrictions on mobility and economic activities imposed by governments due to the COVID-19 pandemic have significantly affected waste production and recycling patterns in cities worldwide. This effect differed both between cities and within cities as the measures of confinement adopted by governments had diverse impacts in different areas of cities, depending on their characteristics (e.g., touristic, or residential). In the present work, mixed waste collection areas were created, based on waste collection points, that define spatial units in which contextual data such as tourism and residential characteristics were aggregated. The difference in mixed waste collected compared with previous years was analyzed along with the impacts on recycling due to the modification in operations regarding waste collection during the lockdown. The results showed that despite the suspension of the door-to-door recycling system during the lockdown, this did not translate into an increase in the production of mixed waste, and the recycling levels of previous years have not been reached after the lockdown, indicating a possible change in recycling habits in Lisbon. The touristic and non-residential mixed waste circuits presented significantly reduced mixed waste production compared to the non-pandemic context. Also, tourist, mobility, and economic activity were measured to understand which factors contributed to waste production changes during the COVID-19 pandemic. While little evidence of a relationship with these exogenous variables was found at the citywide level, evidence was found at the waste collection circuit level.

1. Introduction

At the onset of the COVID-19 pandemic, many countries implemented constrictive measures to individual mobility, services, and economic activities (Agamuthu and Barasarathi, 2021; Mihai, 2020; Sun et al., 2020) in order to control the pandemic outbreak. Naturally, such restrictions introduced several abrupt changes to cities. As a result, the impact on waste production and management was reported worldwide (Nghiem et al., 2020; Patrício Silva et al., 2020; Sarkodie & Owusu, 2020; Vanapalli et al., 2021), with a particular focus on cities and urban areas (Cordes & Castro, 2020; Fan et al., 2021; Y. Liu et al., 2020; Urban & Nakada, 2021). While cities occupy just 2% of the Earth’s surface, they are responsible for the production of 80% of the world gross domestic product; consume 75% of the natural resources; produce 50% of global waste; and are responsible for the emission of 60 to 80% of greenhouse gases at a global level (UNEP, 2017). Unsurprisingly, improving waste management in urban environments is essential to achieving the environmental sustainability targets set by the EU and the UN (da Silva et al., 2019; Malinauskaite et al., 2017). Indeed, policymakers have seen recycling as a possible way to mitigate the growth in waste production in cities, as part of promoting a more circular economy (Zeller et al., 2019).

The lockdown restrictions implemented because of the COVID-19 pandemic not only impacted the volume of waste produced but also its spatial distribution and frequency. These changes pose natural challenges to city planners and officials (Fan et al., 2021; Hantoko et al., 2021) and raise questions about the impact on their ongoing policy efforts. Indeed, Sinha et al. (2020) suggested that waste production has shifted from industry and commercial centers to residential areas, a conclusion that is in line with the Solid Waste Association of North America (Kulkarni & Anantharama, 2020). Sinha et al. (2020) also reported that industrial and commercial waste production suffered a decrease due to the slowdown of economic activity, along with a reduction in recycling activities that led to challenges in the collection and disposal of municipal waste. Besides this, the announcement of lockdowns and travel restrictions led to a drop in waste generation, especially in cities with high levels of tourism (Liang et al., 2021).

However, the context seems to play an important role in determining
the impact of the pandemic on a city’s waste production. Fan et al. (2021) reported that the amount of household waste produced in Shanghai (China) decreased by 23%, while in Brno (Czech Republic), there was an increase of 1% of household waste and a decrease of 40% in business and industrial waste. Overall, Chinese municipal waste production saw a decrease of 30% among medium and large cities (Kulkarni & Anantharama, 2020). The municipal solid waste deposited in landfills in India was reduced between 20% and 40% (Somani et al., 2020). Landfill waste increased 34.7% in Tehran (Iran) (Zand & Heir, 2020), and between February and March, the cities of Kenhira and Tighassale (Morocco) reported a decrease in municipal solid waste production between 2% and 10% compared to the same period in 2019 (Ouhsine et al., 2020). In Europe, the city of Milan (Italy) saw a reduction of 27.5% in total waste production, with 20% in paper and 16% in glass and plastic (AMSA, 2020). The city of Trento (Italy) measured a reduction of 19.5% of municipal solid waste compared with the average value for March over the last ten years (Ragazzi et al., 2020). Waste production in Barcelona (Spain) was reduced by 25% in tourist and commercial activities, along with a reduction of 20% for paper, plastic, and glass, while unsorted waste was reduced by 12%. In the metropolitan area of Paris (France), the decrease in household waste was about 32% in April 2020 compared to a typical period without restrictions (ACR+, 2020). These differences, and their relatively high magnitude, demonstrate the necessity to assess not only the impact of waste production in cities but also their consequences and lasting impact. There is a particular need to assess the consequences of the pandemic on citizen recycling and waste production behaviors across the short, medium, and long terms (Richter, Ng, Vu, et al., 2021).

In Portugal, the first state of emergency, and consequent lockdown, was declared on March 19, 2020, and lasted until May 2, 2020. During that period, measures included restrictions to individual mobility, economic activities, and mandatory remote work. Waste collection, treatment, and disposal processes were adapted to align with the recommendations from the Portuguese Directorate-General for Health to deal with the first lockdown and to guarantee minimum sanitary conditions. The city of Lisbon suspended door-to-door recycling collection until June 1, 2020, and the mixed waste collection was reduced to a maximum of three times per week, which affected 37% of the waste collection circuits, which had a frequency of collection up to 7 times per week.

Here, we build on the existing literature to explore how COVID-19 impacted waste production in the city of Lisbon (Portugal). Lisbon is the capital of Portugal, with a population of 544,581 inhabitants (INE, 2021a) living in an approximately 100 km² area. Its daily population increases 70% due to the commuting population (INE, 2011). Moreover, in 2017, 2018, and 2019, Lisbon registered 12,553,476; 13,184,470; and 13,985,262 overnight stays in tourist accommodation respectively (INE, 2021c), demonstrating the importance of tourism to the Lisbon population dynamics.

We studied weekly waste production data between 2017 and 2020 both at the city level and individual waste collection circuit areas, which were estimated from the waste collection points of each circuit through Thiessen polygons. We characterized the periods before, during, and after lockdown. We controlled the analysis for the impact of lockdown on waste production, tourism, residential and office intensity, as well as temporal, geographical, and seasonal trends in each area of the city. Therefore, this work contributes to the existing literature by providing a high-level geographic and temporally detailed analysis regarding the impact of COVID-19 on waste production.

We present novel data and empirical analysis highlighting the importance of further understanding the spatial heterogeneity of such events’ impact on citizens’ recycling and waste generation habits during and after their occurrence. We show that COVID-19 led to a decline in waste collected, the magnitude of which depended on the intensity of tourism and residential housing. Moreover, after the lockdown measures were lifted, the volume of waste produced did not return to previous levels, and the upward trends in recycling waste observed in the prior years were not recovered even after controlling for variations in tourism. These changes raise the possibilities of longer-term indirect effects from the implemented policies in the recycling habits of Lisbon inhabitants, as indicated by Ikiz et al. (2021), in waste production perception among the residents of Ontario (Canada), during the COVID-19 pandemic.

Insights on waste production changes resulting from external events are essential for city planners to react to future scenarios adequately and adopt appropriate and efficient policies in line with the city’s heterogeneity.

1.1. Factors influencing waste production

The literature identifies that waste production can be affected by external factors which transcend the standard patterns found in the day-to-day waste deposition. Several factors such as population income or Gross Domestic Product (GDP) (Dangi et al., 2011; C. Liu & Wu, 2010; Namilis & Komilis, 2019), population size (Estay-Ossandon & Mena-Nieto, 2018), the average age of the population (Callan and Thomas, 2006), education and household size (Muttar et al., 2019) have been pointed out in the literature as affecting waste production. An additional factor that has not been widely studied is tourism (Diaz-Farina et al., 2020). Indeed, the fluctuations in tourist numbers can be one of the main drivers in waste generation (Estay-Ossandon & Mena-Nieto, 2018) in touristic locations. For example, small businesses related to tourism, hotels, restaurants, and cafés constitute the main driver for food waste generation in touristic locations (Wang et al., 2021). As tourism is associated with holidays and special events, these also impact short-term fluctuations of waste generation (Han et al., 2018; Johnson et al., 2017).

1.2. Spatial analysis of waste production

Current studies on COVID-19 have focused on comparing the impact between different countries, regions, or cities/municipalities (Ouhsine et al., 2020; Richter, Ng, Vu, et al., 2021; Zhou et al., 2021). Such a choice of granularity aligns with the literature on waste generation, where few studies have explored higher spatial granularities (Cheniti et al., 2021). The partition of a city into smaller spatial units is traditionally done through administrative or statistical divisions, such as household (Villalba et al., 2020) or census blocks (Blazquez & Paredes-Belmar, 2020). For instance, Johnson et al. (2017) developed a gradient boosting model to predict waste generation at the level of census sections in the city of New York (USA); Solano Meza et al. (2019) used machine learning models to predict waste production at the level of waste collection zones in the city of Bogota; Mushtaq et al. (2020) analyzed the spatial–temporal variation and forecasting of municipal solid waste in the city of Srinagar (India) at ward level.

However, alternative approaches that break down such administrative constructs can also be achieved by using methods, such as Thiessen polygons (Karimi et al., 2020; Richter et al., 2019; Richter, Ng, Karimi, & Li, 2021; Zhang et al., 2015) or Standard Deviational Ellipses (Richter, Ng, Karimi, & Chang, 2021).

As our interest is examining a higher level of detail than typical administrative zones, we used waste collection point locations and the circuits of waste collection vehicles to divide the city into waste collection areas using Thiessen Polygons. This methodology is detailed in Section 2.

1.3. The impact of COVID-19 in cities mobility

Glaeser et al. (2020) estimated that for every ten-percentage point fall in mobility in New York and four other U.S. cities, there was a drop of 19% in COVID-19 cases per capita. Unsurprisingly then, lockdown measures often involved restrictions to mobility within and between cities. Changes in mobility generated substantial variations in waste
generation. Cai et al. (2021) identified changes to individual mobility and consumer behavior as the main drivers behind the decrease in waste production in Trento, Italy, and Montreal, Canada.

It is pertinent to point out two distinct dimensions of mobility that need to be accounted for when studying the impact of mobility in waste production. One relates to individuals commuting from suburbs into the city, which was reduced significantly due to measures such as mandatory remote work. In Santander (Spain), the overall mobility, number of public transport users, and traffic accidents decreased 76%, 93%, and 67%, respectively (Aloi et al., 2020). Such phenomenal decreases in activity naturally introduced changes which are essential to account for in waste production in cities.

Another relevant dimension of mobility is that of the flow of tourists between cities. COVID-19 travel mobility restrictions imposed between countries affected tourism flows significantly and, therefore, had a proportional impact on the economic activity of regions largely dependent on tourism (Güliz Ügür & Akbyık, 2020): restaurants, hotels, cultural events, and trade fairs (Iloque et al., 2020). It is noteworthy to mention that the effect was dual in that it both affected the demand and supply side, as traveling bans were often applied in both directions.

2. Materials and methods

We used data from the Lisbon municipality Urban Hygiene Department on the volume of waste collected in Lisbon between January 1, 2017, and October 31, 2020. Each observation corresponds to the waste collection on the volume of waste collected in Lisbon between January 1, 2017, and October 31, 2020.

For mixed waste, 23,343 georeferenced collection points were grouped into 114 collection circuits for which location data is available, from the total of 291 mixed waste collection circuits. Each circuit is regularly covered by waste collection vehicles; see Fig. 1 A for the spatial distribution of Lisbon’s mixed waste collection points. For our analysis, data on waste collected per circuit was aggregated weekly to address differences in collection frequency and weekday vs. weekend dynamics.

In the case of mixed waste collection, data is not reported at the collection point level. Instead, it is aggregated by the total collected in a single load from a waste collection vehicle over a circuit, so only the total waste collected from multiple collection points on a single journey was recorded. Collection areas were derived for each circuit from the collection points using Thiessen polygons to deal with this issue and relate the mixed waste collected at the circuit level to the different city characteristics (Aurenhammer, 1991). Each polygon corresponds to the collection area associated with a collection point. In doing so, we were able to associate circuits with areas in the city. Fig. 1B shows an example of the Thiessen polygons associated with a sample of collection points. Circuits presenting spatially dispersed patterns and areas<1 ha were dissolved into the adjacent circuit area with the longest adjacent border.

| Waste Type | Number of Circuits | Number of Loads | Total Waste Collected (tons) |
|------------|--------------------|----------------|----------------------------|
|            | 2017               | 2018           | 2019                        | 2020                        |
| Mixed      | 291                | 184,312        | 234,746                     | 244,996                     | 243,719                     | 183,579                     |
| Paper      | 141                | 36,520         | 18,004                      | 20,783                      | 22,108                      | 13,665                      |
| Plastic    | 109                | 27,474         | 11,388                      | 12,638                      | 13,519                      | 8,570                       |
| Glass      | 172                | 18,878         | 14,330                      | 15,154                      | 16,120                      | 10,703                      |

1. Data only available until October 31.

In summary, we created 97 mixed waste collection areas for 97 circuits (Fig. 1C).

A similar issue arose with the data in terms of recycled waste. However, in this case, we also did not have information about the location of the collection points, nor the collection points registered to each load and corresponding collection circuit. Hence, it was impossible to map recycled waste to city regions.

Additional data was collected to link the observed variations in collected waste during the COVID-19 pandemic with the city characteristics that may influence waste generation, such as the intensity of tourist activity, economic activity, mobility, and residential housing. For this purpose, we collected data on the location of cultural spots and cultural/sports events collected from the Lisbon Open Data Portal (CML, 2018); the number of tourist establishment beds, the capacity of local accommodation users, collected from the Open Data Portal of Portugal Tourism (Turismo Turismo de Portugal, 2019); and tourist establishment bed and room occupancy from Statistics Portugal (INE, 2021c); the number and location of Airbnb reviews (Inside Airbnb, 2016); the location of restaurants, bars, cafes, and markets retrieved from the Open Street Maps project (OSM, 2004); consumer confidence index from Statistics Portugal (INE, 2021b); changes in workplace and residence occupancy resulting from the pandemic from Google (Google, 2020); and the number of exclusively residential, mainly residential and non-residential buildings, collected from the 2011 Portuguese census (INE, 2011).

A Seasonal Auto-Regressive Integrated Moving Average (SARIMA) (Box et al., 2008) model was fit to waste production data to create an estimate of the mixed waste production for 2020 for each waste collection circuit, in the absence of the pandemic and lockdown. The gap between the predicted waste production values and the observed ones was computed through the Mean Absolute Percentage Error (MAPE) (de Myttenaere et al., 2016), which provided a measure of the magnitude of the differences between the waste produced in a pandemic and non-pandemic context. Ordinary Least Squares models (Hutcheson, 1999) were used to evaluate the relation between touristic and residential areas and the gap observed in each waste collection circuit. These variables were selected based on the literature review and the time frequency at which they were recorded. Where variables were not available at a weekly granularity, we took a naïve disaggregation of the monthly variables.

We tested several Seasonal Auto-Regressive Integrated Moving Averages with Exogenous factors (SARIMAX) models to analyze waste and recycling time-series trends and the relationship to exogenous explanatory variables regarding waste production. We computed the Akaike Information Criterion Corrected (AICc) (Hou et al., 2018) to measure the fit and quality of the SARIMAX models and to measure the predictive power and guard against overfitting. Additionally, we assessed the MAPE over a test section of data excluded from the model fitting process. This approach allowed us to test for the factors contributing to waste production at the citywide and the individual circuit level and differentiate their influence from other factors such as seasonality.

3. Results and discussion

Fig. 2A and Fig. 2B compare the amount of waste collected weekly during the analysis period for mixed waste and recycled waste, respectively. Moreover, Fig. 2A compares the observed values of mixed waste for 97 circuits (dark red) with the results of a SARIMA model (light red dashed) trained with data prior to the pandemic onset (light red full line). The SARIMA model provides a baseline scenario of the expected waste production not accounting for the COVID-19 pandemic effects, meaning it represents the expected mixed waste that would be produced if the pandemic had not occurred. Note that with the SARIMA model, we are not controlling for external and exogenous factors that might help explain and predict the temporal trends in waste collection (e.g., number of residents and number of tourists or weather patterns).
Fig. 1. Spatial distribution of collection points and creation of collection circuit areas. A) Spatial distribution of mixed waste collection points. B) Example of the Thiessen polygons created for each one of the collection points (represented by the black dots). Colors indicate different collection circuits. C) Collection circuit areas estimated from the Thiessen polygons.

Table 2 compares the trends in waste collected for the different types of waste before, during, and after the lockdown period. It is possible to observe that the mixed waste before the lockdown presented a decreasing trend, while there is a slightly positive trend for the other types of waste. During the lockdown, there was a significant increasing trend in the production of mixed waste and a slightly increasing trend for glass. This higher increase for mixed waste can be attributed to the shutdown of the door-to-door recycling collection, which may have led people to place recyclable waste in mixed bins. Considering that the glass collection continued to be made in the same form prior to the lockdown, the increase in trend is notable. There was a slight decrease and increase in the trend for plastic and paper, respectively, but both are not statistically significant. After the lockdown, a rapid recovery in the collection of mixed waste is observed. However, pre-lockdown waste production levels have not yet been obtained. The same pattern is also observed for plastic and paper, albeit at a smaller magnitude, while for glass, the trend disappears and becomes flat.

It should be noted that medical waste is not incorporated in this dataset, as the household waste collection services do not collect it. Indeed, this is an essential dimension as medical waste production increased substantially due to the pandemic. However, the obligation of using masks may have contributed to the increase in the production of mixed waste after the lockdown (i.e., May 2). As a reference and following the methodology Sangkham (2020) proposed, an estimated 435,881 face masks were used daily in Lisbon. Considering that each mask weighs 3.5 g, this corresponds to a total of 1.5 t of masks disposed in waste daily and 10.5 t weekly.

Fig. 3A shows the difference, or the gap, between the collected mixed waste and the value predicted by the SARIMA model (see Fig. 2A). We have detailed the specifications of the SARIMA model in Appendix A. Our focus is on the period after March 2020. The most remarkable drop in mixed waste was recorded during the lockdown, although the drop is less evident in the first week of April, probably due to the Easter holidays (Easter was on April 12). The gap after the lockdown (i.e., May 2) increased, especially after the middle of May until the first week of June. The gap decrease during the lockdown and until the middle of May could be related to the shutdown of the recycling door-to-door collection service, which could have led to an increase in mixed waste production. Until the end of October, the gap decreased gradually, but without reaching the predicted level of mixed waste predicted by the SARIMA model (i.e., the expected mixed waste production without the pandemic). These results could be an indication that Lisbon citizens changed their recycling habits. Indeed, new routines such as remote work and the decrease of inbound tourists to Lisbon are two changes worth mentioning, and these trends should be monitored into the future. Fig. 3B shows the year-to-year variation in collected waste for mixed and recycled types and, thus, presents an alternative characterization to that shown in Fig. 3A. In general, the year-to-year variation was positive until the lockdown, although values have been declining over time (see Table 3). The values show a lower decline for mixed waste, plastic, and glass when compared with paper. All waste types saw a decrease in the volume collected between March and May during the lockdown period. The most negligible impact was seen in mixed waste followed by glass, with a more considerable decrease seen in plastic and paper waste production. This result is not surprising, as the mixed waste collection was not suspended but instead restricted. Glass is collected in a different manner than the other two types of recycled waste (paper and plastic). Plastic and paper are collected through bins in the city of Lisbon, which are typically the responsibility of each building condominium. These were significantly affected by the suspension of the door-to-door waste collection, while glass, on the contrary, is collected through deposit points located in the street (i.e., public areas). Thus, residents were not necessarily restricted in depositing glass, and the collection was also not affected. The municipality resumed the door-to-door collection of plastic and paper on June 1 and maintained the frequency of the collection of mixed waste three times per week. After June 1, all waste types present a similar pattern with a positive trend, despite their negative values in year-to-year variation, never achieving the pre-pandemic values seen between 2017 and 2019. The only exception was for plastic and paper, which at the end of October recorded a positive variation of 5% and 9% respectively when compared with the same period in the previous year (2019).

Hence, it is not surprising to see that the different implemented measures had a different impact on the magnitude of the reduction of the
different types of waste collected. The lower magnitude impact of mixed waste can also be explained by the fact that citizens were implicitly incentivized to deposit paper and plastic as mixed waste, a behavior that might have also spilled over to glass. This idea is reinforced by the fact that we do not observe a substantial and abnormal increase in recycled waste collected after the lockdown.

The negative ratios in the year-to-year variations after June allow us to quantify the magnitude (or weight) of “Tourism” and other similar externalities (e.g., industrial and services activity) in waste production, in contrast with the waste endogenously produced by the city (e.g., residents and inhabitants with fixed household and hospitals). Moreover, in that sense, we see that the overall impact is in the order of 10%. Nevertheless, how does the impact differ throughout the geography of the city? Were all regions affected equally?

Unfortunately, due to the structure and quality of the data, we could only explore such questions for mixed waste. Fig. 4A presents a matrix of correlations between different variables that quantify the intensity of tourism (i.e., number of touristic establishment beds and local accommodation users, the number of cultural events, restaurants, cafes, bars, markets, and cultural spots) as well as residential housing use (i.e., the number of exclusively residential, mainly non-residential and mainly residential buildings).

The correlation with the gap is positive and highest for the tourism related variables and the number of mainly non-residential buildings, highlighting the effects of the reduction in mixed waste produced in circuits with tourism activity and no residential characteristics. Due to the lockdown and the mandatory remote work policies during the studied period, the number of mainly residential buildings in the mixed waste circuits presented a low positive correlation, while the number of exclusively residential buildings presented a low negative correlation,
indicating that the reduction in waste production was lower in exclusively residential areas.

We performed a linear regression with the ordinary least squares (OLS) approach to distinguish the effects of the different variables on the "gap" in waste production. We have provided the results in Table 4. The first model, containing all the identified variables, achieved an adjusted $R^2$ of 0.46; however, most variables are not significant, and the model suffers from multicollinearity. In particular, the variables representing the number of Restaurants & bars and the Number of Mixed non-Residential Buildings are too closely related to the other tourism variables such as the Number of tourist establishment beds. After removing insignificant variables and variables with high multicollinearity, we found model 2, which contained only two variables – the Total Number of Tourist Beds and the Number of Mixed Residential Buildings – achieving an $R^2$ of 0.45. After removing variables with high multicollinearity, the unstandardized regression coefficients for both the local accommodation and tourism beds were significant and very similar. Combining these two variables into total tourism beds did not significantly reduce $R^2$ and improved the generality of the model. There is some evidence of non-linearity in the residuals of this model and between 1 and 3 potential outliers that reduce the normality of the residuals. However, removing these outliers does not significantly affect the results and particularly the interpretation of the coefficients. As we did not intend to use this model for forecasting but only to identify explanatory variables, we did not investigate these issues further.

As an alternative measure of the COVID-19 effect, model 3 performed a regression on the average year-to-year reduction in mixed waste production in the period after the lockdown (June-Oct 2020). This
model produced similar results, with the slight difference being that the count of residential buildings replaces the count of mixed residential buildings as a significant predictor of the effect on waste production. These results show conclusively that different city areas suffered a different magnitude in the decrease of waste produced during the lockdown, according to their characteristics. However, they also recovered differently after the restrictions were lifted: high tourism intensity areas with low residential housing were the ones that observed the sharpest declines and did not return to pre-pandemic level of waste production.

We can also use the time series model to explore the causal link between the COVID-19 pandemic, lockdown, and changes in waste production behavior. For example, are changes specific to lockdown periods? Or do they persist during periods where the case counts are higher as workers choose to remain home and tourism numbers are lower? Can the reductions in tourism or consumer spending seen during this period explain reductions observed in waste production?

Firstly, we tested the addition of explanatory variables to the time series model fit on data prior to 2020 and tested the fit of such models and their predictive accuracy over the 2020 period. Based on the literature review of waste production drivers, we tested several variables, including the number of events held, the number of holidays, tourist bed occupancy rate, tourist room occupancy rate, the count of posted AirBnB reviews, and the level of consumer confidence. None of these variables improved the model as measured by AICc, and only the coefficients for holidays and tourism room occupancy were significant at the 5% level (for brevity, the complete results are included in Appendix B). The model that incorporates consumer confidence significantly improves

---

**Table 4**

Regression results for OLS linear regression of the change in waste production (% reduction in mixed waste) in different areas resulting from COVID-19. Model 1 and Model 2 predict the gap during lockdown measured as the percentage of the difference between the actual value and the forecasted value of the SARIMA model, and model 3 measure the average year-to-year variation for the period after the lockdown (i.e., June – October 2020).

| Model 1 | Model 2 | Model 3 |
|--------|--------|--------|
| (SARIMA gap) | (SARIMA gap) | (average YoY gap) |
| Intercept | 15.362 *** | 14.774 *** | 10.946 *** |
| No. rest. & bars | 0.051 | 0.000 | 0.000 |
| No. cultural spots | 0.188 | 0.210 | 0.091 |
| No. touristic estab. beds | 0.001 | 0.901 | 0.000 |
| No. local accom. beds | 0.002 * | 0.385 * | 0.000 |
| Total tourism beds | 0.003 *** | 0.829 *** | 0.004 *** |
| No. Events | 0.004 | 0.053 | 0.000 |
| No. residential buildings | −0.002 | −0.064 | −0.011 *** |
| No. mixed non-res. bdgs | 0.126 | 0.231 | 0.000 |
| No. mixed residential buildings | −0.045 *** | −0.380 *** | −0.037 *** |
| F-statistic | $F_{(8,86)} = 11.05$ *** | $F_{(2,92)} = 39.39$ *** | $F_{(2,92)} = 52.45$ *** |
| Adjusted R² | 0.46 | 0.45 | 0.52 |

**Note:**

- **p < 0.01.**
- **p < 0.05.**
- **p < 0.001.**
MAPE by reducing the forecast waste production over the lockdown period. However, this result cannot be considered robust with the coefficient on the variable not significant and an increase in AICc when this variable is included.

Next, we repeated the analysis, including the lockdown period in the training dataset, and used the final three months of data as the test dataset. This approach allowed us to examine additional measures associated with the pandemic (the lockdown period, the period without recycling, the number of daily new cases, changes in workplace occupancy, and changes in residential occupancy) in an attempt to separate effects specific to, for example, tourism from the effects directly associated with the lockdown. In this case, we found both the lockdown dummy variable and the number of holidays significant and improved the model as measured by AICc. We then included these variables in the model and tested the inclusion of the other exogenous factors to see if they added explanatory power over what was explained by the lockdown. The results are reported in Table 5. We can see in this case that controlling for the period where recycling was suspended improved the model as measured by AICc, and all coefficients are significant. This model captured that fact that the lockdown itself reduced the production of mixed waste. However, accounting for the overlapping period where recycling was suspended, the production of mixed waste increased. Without this distinction, the measured effect of lockdown or the reduction in waste production is much lower. While several tested factors have significant coefficients in this larger combined model, they typically do not improve the AICc, creating uncertainty as to if they are adding to the model’s explanatory power and not overfitting. It is interesting to note that the inclusion of tourist bed occupancy is significant in addition to the lockdown and improved the MAPE in the test period after the end of lockdown, suggesting the lingering effect of the reduction in tourism could be explanatory after the immediate lockdown period.

Finally, while we did not find solid relationships for the exogenous variables at the citywide level, we could find evidence of relationships at the individual circuit level. For example, first, we examined circuits with the most significant reduction in waste production resulting from COVID-19. In six of the ten circuits with the most considerable reduction in waste production, adding tourism as measured by AirBnB review count to the model was significant; it improved AICc and improved the prediction in the later 2020 period as measured by the MAPE. However, this was only the case for 20 of the total 95 circuits (see APPENDIX B). We found similarly that four of the top ten, and 17 of the 95 circuits met these criteria for bed occupancy rates. Indicating that while we may not find strong relationships at the citywide level, areas are differently affected by the various factors associated with the pandemic, and tourism is an important component for many of the most affected areas.

Overall, we found that the effect of COVID-19 had significant differences in waste production throughout the city. Information about the intensity of tourism/residential areas can provide good proxies for deploying more adequate and targeted policies for waste management in events that share similarities to the lockdown measures implemented after the COVID-19 onset. This approach to the assessment of mixed waste allows waste management authorities to improve waste collection operations, considering the expected mixed waste that would be produced in a circuit based on a simple classification of the characteristics of different areas. In addition, it provides quantification of the magnitude of waste production changes resulting from lockdowns and restrictions on recycling and collection and hints into the lasting effect of changes in work and waste production behavior. While tourism is likely to return to pre-pandemic levels, teleworking culture may persist in some form and may result in the continuity of the current waste production trend.

The research demonstrates the importance of considering waste production shocks at a high level of geographic granularity. In this study, these predictions were made in a pandemic context. However, the same ideas apply to the regular daily operations where it is possible to optimize the number of trips necessary to collect mixed waste in a particular area of the city.

It should be noted that the current work has several limitations. Firstly, waste collection data is reported by circuit level and not by collection point. Such data collection protocol needs to be revised to offer researchers and city officials better-quality data and minimize errors naturally introduced by spatial inference. Secondly, available socioeconomic and demographic data is outdated as the last census data is from 2011, and updated data would improve the analysis. Thirdly, recycled, and mixed collection points do not overlap, which given the limitations mentioned above on the aggregation level of the data, prevents the same analysis from being conducted with the two datasets.

Future research should build on the geographic differences in waste production identified here and could involve the collection areas’ clustering to find commonalities and differences in how susceptible they are to externalities. This challenge is critical to further our ambition to improve the planning and management of cities with data-driven public policy making.

4. Conclusion

COVID-19 and the ensuing measures to contain its spread impacted the dynamics of cities in many ways worldwide. Here we explored how the lockdown measures implemented in the city of Lisbon (Portugal) impacted waste production for both mixed and recycled waste at a high level of temporal and geographic detail.

We found that waste production in the city of Lisbon suffered a sharp decline during the lockdown period that was under effect between March and May of 2020. However, the magnitude of such decline differed depending on the type of waste and the location within the city.

Table 5
SARIMAX time series model results with different exogenous variables. Coef stands for coefficient.

| Exogenous Variable 1 | Exogenous Variable 2 | Coef 1    | Coef 2    | Coef 3    | AICc   | MAPE  |
|----------------------|----------------------|-----------|-----------|-----------|-------|-------|
| Holidays             | Lockdown             | 2141      | 3.4%      |           |       |       |
| Events               | Holidays             | 2089.1    | 3.8%      |           |       |       |
| Tourism-Bed occupancy| Holidays             | 2091.0    | 3.9%      |           |       |       |
| Tourism-Room occupancy| Holidays             | 2122.9    | 2.3%      |           |       |       |
| Tourism-Air BnB review count | Holidays | 2122.3    | 2.4%      |           |       |       |
| Consumer confidence  | Holidays             | 2122.3    | 2.4%      |           |       |       |
| Workplace occupancy change | Holidays | 2127.3    | 9.2%      |           |       |       |
| Residence occupancy change | Holidays | 2184.1    | 7.5%      |           |       |       |
| Recycling suspended  | Holidays             | 2091.3    | 3.8%      |           |       |       |
| New COVID-19 case count | Holidays | 2157.1    | 6.4%      |           |       |       |

\* p < 0.05.  
\** p < 0.01.  
\*** p < 0.001.
Additionally, the amount of waste produced never recovered to the pre-pandemic levels during the period of study. Recycled waste, which exhibited an upward trend before the onset of COVID-19, did not recover this trend after June 2020, when restrictions were lifted/relaxed. In addition, we separated distinct effects of lockdown policies and restrictions on recycling that co-occurred. This factor allows us to quantify even more significant reductions in waste production due to lockdown measures than would be measured ignoring the simultaneous recycling restrictions and to provide an estimate of the increase in mixed waste production associated with recycling restrictions. These results may potentially signal a shift in the recycling behavior of the citizens of Lisbon. However, the data available for this study did not allow us to reach a conclusive answer on whether that is the case. Further research should be undertaken to examine whether the policies implemented to stop the pandemic outbreak might have impaired the effectiveness of city policies in promoting recycling habits.

Further, we investigated whether the impact of COVID-19 in waste production was similar across the city. Data from the city of Lisbon comes initially aggregated at the collection circuit level, from which collection areas were created by using Thiessen polygons on the collection points that were merged according to the respective waste collection circuit. We showed that depending on the intensity of residential housing and tourism activity, the impact on waste production across the city was not uniform. Higher residential housing areas revealed a lower decrease in waste production, while high tourism intensity areas saw a higher decrease. In addition to the lockdown itself, tourism was identified as an important factor in predicting the level of waste production in areas that faced the most considerable reduction in waste production over the period. These insights show that with access to useful proxies, city officials can develop more targeted and adequate policies for each area, depending on their contextual characteristics in pandemic scenarios or other scenarios that substantially change city dynamics.

Declaration of Competing Interest

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

Acknowledgments

This work was supported by the Connecting Europe Facility (CEF) – Telecommunications sector in the framework of project Urban Co-Creation Data Lab [INEA/CEF/ICT/A2018/1837945]. The research developed by Ian J. Scott was co-financed by the ERDF – European Regional Development Fund through the Operational Program for Competitiveness and Internationalization COMPETE 2020, the Lisbon Portugal Regional Operational Program – LISBOA 2020 and by the Portuguese Foundation for Science and Technology – FCT under CMU Portugal Program, in the framework of project BEE2WasteCrypto [IDT-COP 45933]. The authors would also like to thank the Lisbon Urban Hygiene Department for the provided data used in this paper and the information regarding changes in the waste collection operations during the COVID-19 pandemic in the studied period.

Appendix A: Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2021.12.002.

References

Agamuthu, P., Barasarathi, J., 2021. Clinical waste management under COVID-19 scenario in Malaysia. Waste Management & Research 39 (1_suppl), 18–26. https://doi.org/10.1177/0734242X20970618.

Aloi, A., Alonso, B., Benavente, J., Cordera, R., Echáns, E., González, F., Ladina, C., Lezama-Romanelli, R., López-Parrá, A., Mazzei, V., Perrucci, L., Prieto-Quintana, D., Rodríguez, A., Sainudo, R., 2020. Effects of the COVID-19 Lockdown on Urban Mobility: Empirical Evidence from the City of Santander (Spain). Sustainability 12 (9), 3870. https://doi.org/10.3390/su12093870.

AMSA, 2020. Waste Management and Cleaning Services in Milan during COVID-19. https://www.acrplus.org/images/PROJECTS/COVID-19/AMSA_Waste_management_during_COVID-19.pdf (accessed 23 April 2021).

Aurenhammer, F., 1991. Voronoi Diagrams: A Survey of a Fundamental Geometric Data Structure. ACM Computing Surveys 23 (3), 345–405.

Blasquez, C., Paredes-Belmart, G., 2020. Network dynamics of a household waste collection system: A case study of the community of Renca in Santiago, Chile. Waste Management 116, 179–189. https://doi.org/10.1016/j.wasman.2020.07.027.

Box, G., Jenkins, G., Reinsel, G., 2008. Time Series Analysis, 4th Edition. Wiley.

Cai, M., Guy, C., Héroux, M., Lichtfouse, E., An, C., 2021. The impact of successive COVID-19 lockdowns on people mobility, lockdown efficiency, and municipal solid waste. Environmental Chemistry Letters 19 (6), 3959–3965. https://doi.org/10.1007/s10311-021-01290-z.

Callan, S.J., Thomas, J.M., 2006. Analyzing demand for disposal and recycling services: A systems approach. Eastern Economic Journal 32 (2), 221–240.

Chen, H., Cheniti, M., Brahamia, K., 2021. Use of GIS and Moran’s i to support residential solid waste recycling in the city of Annaba, Algeria. Environmental Science and Pollution Research 28, 34027–34041. https://doi.org/10.1007/s11356-020-10911-z/Published.

CML, 2018. Lisbon Open Data Portal. http://lissobaerta.cml.islimporto.pt/index.php/pt (accessed 13 March 2021).

Cordeiro, C., Castro, M.C., 2020. Spatial analysis of COVID-19 clusters and contextual factors in New York City. Spatial and Spatio-Temporal Epidemiology 34, 100355.

da Silva, L., Manques Prietto, P.D., Pavan Kor, E., 2019. Sustainability indicators for urban solid waste management in large and medium-sized worldwide cities. Journal of Cleaner Production 237, 117802. https://doi.org/10.1016/j.jclepro.2019.11.7802.

Dangi, M.B., Pretz, C.R., Urynowicz, M.A., Gerow, K.G., Reddy, J.M., 2011. Municipal solid waste generation in Kathmandu. Nepal. Journal of Environmental Management 92 (1), 240–249. https://doi.org/10.1016/j.jenvman.2010.09.005.

de Myttenaere, A., Golden, B., Le Grand, B., Rossi, F., 2016. Mean Absolute Percentage Error for regression models. Neurocomputing 192, 38–48. https://doi.org/10.1016/j.neucom.2015.12.114.

Díaz-Farina, E., Díaz-Hernández, J.J., Padron-Fumero, N., 2020. The contribution of tourism to municipal solid waste generation: A mixed demand-supply approach on the island of Tenerife. Waste Management 102, 587–597. https://doi.org/10.1016/j.wasman.2020.10.035.

Estay-Ossandon, C., Mena-Nieto, A., 2018. Modelling the driving forces of the municipal solid waste generation in touristic islands. A case study of the Balearic Islands (2000–2010). Waste Management 75, 70–81. https://doi.org/10.1016/j.wasman.2017.12.029.

Fan, Y.Y., Jiang, P., Henzal, M., Klemsi, J.J., 2021. An update of COVID-19 influence on waste management. Science of the Total Environment 754, 142014. https://doi.org/10.1016/j.scitotenv.2020.142014.

Glaeser, E.L., Gorbach, C., Redding, S.J., 2020. JUR InSight: How much does COVID-19 increase with mobility? Evidence from New York and four other U.S. cities. Journal of Urban Economics 103292. https://doi.org/10.1016/j.jue.2020.103292.

Google (2020). Community mobility reports. https://www.google.com/covid19/mobility/ (accessed 18 August 2021).

Güla Uğur, N., Akınyör, A., 2020. Impacts of COVID-19 on global tourism industry: A cross-regional comparison. Tourism Management Perspectives 36, 100744. https://doi.org/10.1016/j.tmp.2020.100744.

Han, Z., Liu, Y., Zhong, M., Shi, G., Li, Q., Zeng, D., Zhang, Y., Fei, Y., Xie, Y., 2018. Influencing factors of domestic waste characteristics in rural areas of developing countries. Waste Management 72, 45–54. https://doi.org/10.1016/j.wasman.2017.11.034.

Hantoko, D., Li, X., Pariyathamby, A., Yoshikawa, K., Horttanainen, M., Yan, M.I., 2021. Challenges and practices on waste management and disposal during COVID-19 pandemic. Journal of Environmental Management 286, 112140. https://doi.org/10.1016/j.jenvman.2021.112140.

Hoque, A., Shikha, A., Hasanat, M.W., Arif, S., Hamid, A.B.A., 2020. The Effect of Coronavirus (COVID-19) in the Tourism Industry in China. Asian Journal of Multidisciplinary Studies 3 (1), 52–58.

Hou, M., Yang, Y., Liu, T., Peng, W., 2018. Forecasting time series with optimal neural networks using multi-objective optimization algorithm based on AIOC. Frontiers of Computer Science 12 (6), 1261–1263. https://doi.org/10.1007/s11704-018-0905-8.

Hutcheson, G., 1999. The Multivariate Social Scientist. SAGE Publications, Ltd. https://doi.org/10.4135/9781412983935.

Ikiz, E., Maclaren, V.W., Alfred, E., Sivanesan, S., 2021. Impact of COVID-19 on household waste flows, diversion and reuse: The case of multi-residential buildings in Toronto, Canada. Resources, Conservation and Recycling 164, 105111. https://doi.org/10.1016/j.resconrec.2020.105111.

INE (2011). Census 2011. https://censos.ine.pt/xportal/xmimp/ximpCENSOSExppji-0/census2011/apresentacao (accessed 6 April 2021).

INE (2021). Census 2021 – Preliminary results. https://www.ine.pt/scripts/db_census_2021.html (accessed 5 May 2021).
INE. (2021b). Consumers confidence index. https://www.ine.pt/xportal/xmain?xpid=INE&indicxpid=indicadores&indicOrdCod=0001173&contexto=bckeRefItab-tab2 (accessed 28 August 2021).

INE. (2021c). Overnight stays in tourist accommodation by geographic location. https://www.ine.pt/xportal/xmain?xpid=INE&indicxpid=indicadores&indicOrdCod=000857&contexto=bckeRefItab-tab2 (accessed 28 August 2021).

Inside Airbnb (2016). Airbnb reviews. http://insideairbnb.com/index.html (accessed 5 September 2021).

Johnson, N.E., Janiuk, O., Cazap, D., Liu, L., Starobin, D., Dobler, G., Ghandehari, M., 2020. Patterns of waste generation: A gradient boosting model for short-term waste prediction in New York City. Waste Management 62, 3–11. https://doi.org/10.1016/j.wasman.2017.01.037.

Karimi, N., Richter, A., Ng, K.T.W., 2020. Siting and ranking municipal landfill sites in regional scale using nighttime satellite imagery. Journal of Environmental Management 256, 109942. https://doi.org/10.1016/j.jenvman.2019.109942.

Kulkarni, B.N., Anantharama, V., 2020. Repercussions of COVID-19 pandemic on solid waste generation and management strategies. Front. Environ. Sci. Eng. 15 (6) https://doi.org/10.3390/ijerph17155439.

Liu, Y., Gayle, A.A., Wilder-Smith, A., Rockl–Wagner, P., Sarmento et al. 2020. The reproductive number of COVID-19 is higher compared to SARS coronavirus. Journal of Travel Medicine 27, 1–4. https://doi.org/10.1093/jtm/taaa021.

Maliniukaité, J., Jouraha, H., Czajcynska, D., Stanchev, P., Katsou, E., Rostkowski, P., Thorne, R.J., Colin, J., Founsi, S., Al-Mansour, F., Anguilano, L., Krzyzynska, R., López, I.G., Vlasopoulos, A., Spencer, N., 2017. Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe. Energy 141, 2033–2044. https://doi.org/10.1016/j.energy.2017.11.128.

Mihai, F.-C., 2020. Assessment of COVID-19 Waste Flows During the Emergency State in Romania and Related Public Health and Environmental Concerns. International Journal of Environmental Research and Public Health 17 (15), 5439. https://doi.org/10.3390/ijerph17155439.

Mushtaq, J., Dar, A.Q., Ahsan, N., 2020. Spatial-temporal variations and forecasting analysis approach for assessment of waste management cost efficiency in low-population density regions. Sustainable Cities and Society 65, 102583. https://doi.org/10.1016/j.scs.2020.102583.

Nichol, S., Nester, A., Sutherst, R.W., 2021b. An iterative tessellation-based analytical approach to the design and planning of waste management regions. Computers, Environment and Urban Systems 88, 101652. https://doi.org/10.1016/j.compenvurbs.2021.101652.

Richter, A., Ng, K.T.W., Karimi, N., Wu, P., Kashani, A.H., 2019. Optimization of waste management regions using recursive Thiessen polygons. Journal of Cleaner Production 234, 85–96. https://doi.org/10.1016/J.JCLEPRO.2019.06.178.

Richter, A., Ng, K.T.W., Vu, H.L., Kubir, G., 2021c. Waste disposal characteristics and data variability in a mid-sized Canadian city during COVID-19. Waste Management 122, 49–54. https://doi.org/10.1016/j.wasman.2021.01.004.

Sangkhram, S., 2020. Face mask and medical waste disposal during the novel COVID-19 pandemic in Asia. Case Studies in Chemical and Environmental Engineering 2, 100052. https://doi.org/10.1007/s10668-020-00956-y.

Sinka, R., Michelsen, J.D., Ackura, E., Njie, L., 2020. COVID-19’s Impact on the Waste Sector. International Finance Corporation, World Bank Group.

Solano Meza, J.R., Orjuela Yepes, D., Rodrigo-Ibarri, J., Cassiraga, E., 2019. Predictive analysis of urban waste generation for the city of Bogotá, Colombia, through the implementation of decision trees-based machine learning, support vector machines and artificial neural networks. Heliyon 5 (11), e02810. https://doi.org/10.1016/j.heliyon.2019.e02810.

Somani, M., Srivastava, A.N., Gummadiwalli, S.K., Sharma, A., 2020. Indirect implications of COVID-19 towards sustainable environment: An investigation in Indian context. Bioresource Technology Reports 11, 100491. https://doi.org/10.1016/j.btr.2020.100491.

Sun, X., Xiao, Y., Ji, X., 2020. When to lift the lockdown in Hubei province during COVID-19 epidemic? An insight from a patch model and multiple source data. Journal of Theoretical Biology 507, 110469. https://doi.org/10.1016/j.jtbi.2020.110469.

Tourismo de Portugal (2019). Turismo Portugal Open Data Portal. https://datosabertos.turismodeportugal.pt/ (accessed 25 March 2021).

UNEP, 2017. The Emissions Gap Report 2017 - A UN Environment Synthesis Report. United Nations Environment Programme Reports.

Urban, R.C., Nakada, L.Y.K., 2021. COVID-19 pandemic: Solid waste and environmental impacts in Brazil. Science of the Total Environment 755, 142471. https://doi.org/10.1016/j.scitotenv.2020.142471.

Vanapalli, K.R., Sharma, H.B., Ranjan, V.P., Samal, B., Bhattacharya, J., Dubey, B.K., Goel, S., 2021. Challenges and strategies for effective plastic waste management during and post COVID-19 pandemic. Science of the Total Environment 750, 141514. https://doi.org/10.1016/j.scitotenv.2020.141514.

Villalba, L., Donaldo, R.S., Cisneros Bazudlo, N.E., Nortega, R.B., 2020. Household solid waste characterization in Tandil (Argentina): Socioeconomic, institutional, temporal and cultural aspects influencing waste quantity and composition. Resources, Conservation and Recycling 152, 104530. https://doi.org/10.1016/j.resconrec.2019.104530.

Wang, L.-e., Filimonau, V., Li, Y., 2021. Exploring the patterns of food waste generation by tourists in a popular destination. Journal of Cleaner Production 279, 123890. https://doi.org/10.1016/j.jclepro.2020.123890.

Zand, A.D., Heir, A.V., 2020. Emerging challenges in urban waste management in Tehran, Iran during the COVID-19 pandemic. Resources, Conservation and Recycling 162 (July), 105051. https://doi.org/10.1016/j.resconrec.2020.105051.

Zeller, V., Towa, E., Degrez, M., Achten, W.M.J., 2019. Urban waste flows and their potential for a circular economy model at city-region level. Waste Management 83, 83–94. https://doi.org/10.1016/j.wasman.2018.10.034.

Zhang, G., Lin, T., Chen, S., Xiao, L., Wang, J., Guo, Y., 2015. Spatial characteristics of municipal solid waste generation and its influential spatial factors on a city scale: a case study of Xiamen, China. Journal of Material Cycles and Waste Management 17 (2), 399–409. https://doi.org/10.1007/s10161-014-0257-7.

Zhou, C., Yang, G., Ma, S., Liu, Y., Zhao, Z., 2021. The impact of the COVID-19 pandemic on waste-to-energy and waste-to-material industry in China. Renewable and Sustainable Energy Reviews 139, 110693. https://doi.org/10.1016/j.rser.2020.110693.