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The impact of successive COVID-19 lockdowns on people mobility, lockdown efficiency, and municipal solid waste

Mengfan Cai¹ · Christophe Guy² · Martin Héroux³ · Eric Lichtfouse^{4,5}  · Chunjiang An¹ 

Abstract

The COVID-19 pandemic has induced many issues for all societal sectors, in particular in the production and disposal of municipal solid waste. This may be because successive easing and reimposing of lockdown measures have deeply changed people's movements, consumers' behaviors and waste management. Previous studies have focused on the short-term effects of lockdowns on waste changes, yet there is little knowledge on waste variations during successive lockdowns and unlock-ing of various lockdown intensities. Moreover, the efficiency of lockdown and its relation to people's mobility in different countries are still not clear. Here, we studied the variations of amount and composition of municipal solid waste before the pandemic in 2019 and during the pandemic in 2020–2021 in USA, Brazil, Canada, UK, France and Italy. We used a stringency index and a composite mobility index to assess the lockdown intensity and people's movements. Results show that the mobility index sharply decreased with lockdown intensity, and enforcing measures were more efficient in France and Italy. Compared to 2019, prolonged lockdowns caused larger decreases in the quantity of commercial and construction wastes versus household waste. The initial implementation of lockdown or unlocking measures promoted inhabitants' consumption, generally leading to the increased waste amount, by about 9% for Trento and 12% for Montreal at the beginning of lockdown, respectively. Moreover, larger variations in the waste amount in Trento, from –25.3 to 9.8%, were in line with higher lockdown intensity compared to those in Montreal, from –9.5 to 12.7%, affected by people's mobility, consumers' behaviors and waste management.

Keywords COVID-19 · Lockdown · Resurgence · Municipal solid waste · Waste amount and composition

Introduction

The coronavirus disease 2019 (COVID-19) reported 172 million confirmed cases and 3.7 million deaths by June 3, 2021, globally (Google News 2021). The most affected

countries included the United States (USA), Brazil, India, Mexico, the United Kingdom (UK), Italy, Russian, and France (Google News 2021; Huo et al. 2021). Protective measures such as mask wearing, traffic restriction, social distancing, and home isolation have been globally implemented to reduce the spread of coronavirus (Wang et al. 2021). Many regions have experienced lockdowns since the beginning of this pandemic in March–April 2020, followed by gradual unlocking since May 2020. After this first pandemic wave, increasing economic and social activities have induced a second pandemic wave, as expected, in Euro-American countries since July 2020, and, in turn, new restrictions and lockdowns were imposed since September 2020. Lockdown periods have generally had positive impacts on environmental quality, with a notable decrease in urban air pollution (Wang et al. 2020a; Zambrano-Monserrate et al. 2020), yet there are concerns about the effect of lockdown on waste generation and recycling (Kulkarni and Anantharama 2020). Municipal solid waste (MSW) is an unavoidable by-product

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of human activity, and its recycling and recovery can facilitate the progression of a circular economy (Das et al. 2021). However, the COVID-19 pandemic has brought MSW systems severe challenges, such as the quantity variation and composition change of MSW (Vaverková et al. 2020; Vu et al. 2021; Yousefi et al. 2021). For instance, a significant escalation of medical waste was observed in some Asian cities and countries, such as India, during the lockdown compared to levels before the pandemic (Somani et al. 2020; You et al. 2020; Zand and Heir 2020). Nonetheless, the lockdown caused only a small waste rise in Singapore and even substantial reductions of MSW in India and Shanghai (Fan et al. 2020; Somani et al. 2020). Therefore, the effect of lockdown on waste dynamics can vary among regions due to distinct geographical, economic, and sociological characteristics. In particular, MSW production may be influenced by lockdown intensity and people's movements. Most studies mentioned above investigated the short-term effect of single lockdown on waste variations. The efficiency of lockdown and its relationship to people's mobility in different countries are still not clear. Here, we studied the effect of lockdown measures on people mobility, and the influence of successive lockdowns on waste variations in Euro-American regions.

Experimental

We selected six countries in Euro-America, including USA, Brazil, Canada, UK, France and Italy, in consideration of their large number of confirmed cases and deaths. Information on the timing and stringency of lockdown measures across the world was collected from the Oxford Coronavirus Government Response Tracker (OxCGRT 2021) and the COVID-19 Community Mobility Reports (2021). We also collected documents that provided the MSW amount in 2020–2021 or the variations in MSW amount between 2019 and 2020–2021 from news and municipal information. The City of Montreal in Canada and the City of Trento in Italy were selected as representative cities for America and Europe, respectively, to analyze the influence of varying pandemic lockdowns on waste variations during different lockdown periods (Trento Municipality 2021; City of Montreal 2020).

Lockdown intensity and people mobility

During the pandemic, the government lockdown intensity and people's movements changed with varying lockdowns, resulting in variations in the amount, composition and management of MSW. Here, we adopted a stringency index (S_l , dimensionless) and a composite mobility index (M_i^j , dimensionless) to represent the government lockdown intensity and people's movements, respectively. The S_l was

comprehensively calculated by nine response indicators (OxCGRT, 2021):

$$S_l = \frac{\sum_{j=1}^9 I_j}{9} \quad (1)$$

where I_j is the sub-index score for any given indicator (j), such as closures of school, workplace, and public transport; restrictions on public events, public gatherings, internal movements, international travel, and public information campaigns; and stay-at-home requirements. The detailed equation for the S_l can be found at OxCGRT (2021). In this study, the lockdown intensity was evenly classified into five levels based on the S_l , that is, level 1, 2, 3, 4 and 5 for S_l of 0–20, 20–40, 40–60, 60–80 and 80–100, respectively.

If lockdown measures vary at the subnational level, S_l is shown as the response level of the strictest subregion. This may result in the overestimation of the lockdown intensity of some cities. Mobility trends can show how peoples' movements have changed throughout the pandemic; thus, they were adopted to describe the specific lockdown intensity at different spatial scales. According to the COVID-19 Community Mobility Reports (2021), the mobility change (M_i^j , %) in visitor numbers (N_i) to specific categories of location between a COVID-19 pandemic period (j) versus the baseline period before the pandemic was measured using Eq. 2:

$$M_i^j(\%) = \frac{N_{COVID_i^j} - N_{baseline_i^j}}{N_{baseline_i^j}} \times 100\% \quad (2)$$

where i indicates one of six broad categories of location, including residential places, grocery and pharmacy stores, workplaces, parks, transit stations, and retail and recreation. In this study, principal component analysis (PCA) was conducted using SPSS 16.0 to generate a composite mobility index for the comparison of different regions (Wang et al. 2020b). All the statistical analyses and figures were conducted and prepared using Microsoft Excel 2020, SPSS 16.0, and Origin Pro 9.1.

PCA results are shown in Table 1 and Supplementary Material's Tables S.1–6. Table S.1 shows that there is a linear correlation between six variables because the correlation coefficient between each group of variables is generally greater than 0.3. The overall KMO test coefficient is 0.707; the KMO test coefficient of each variable is greater than 0.5; and Bartlett's test result is $p < 0.001$ (Tables S.2–S.3). These results mean that the data structure is reasonable, and the data can be extracted by principal components. Table 1 and Table S.4 suggest that only the eigenvalue of the top one principal component in this study is greater than 1, explaining 69.318% of the total data variation. Tables S.5–S.6 indicate the high explanatory ability of this principal component to six variables. Thus, the extracted principal component,

Table 1 Total variance explained

Component	Initial eigenvalues			Extraction sums of squared loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.159	69.318	69.318	4.159	69.318	69.318
2	0.981	16.355	85.673			
3	0.528	8.808	94.481			
4	0.201	3.346	97.827			
5	0.088	1.470	99.297			
6	0.042	0.703	100.000			

Extraction method: principal component analysis

Table 2 MSW amount (tons) in Montreal and Trento in 2019

City	Waste amount (tons)			
	Organic	Recyclable	Others	Total
Montreal	372, 168	266, 855	281, 865	920, 888
Trento	17, 695	19, 546	17, 480	54, 721

the composite mobility index (M^i , dimensionless), could be directly used as a newly generated variable for further data analysis.

Amount of municipal solid waste

In this study, organic and recyclable wastes were the major compositions, accounting for around 32% and 36% of the total waste amount (tons) in Trento and 40% and 29% in Montreal in 2019, respectively (Table 2). The recyclable waste included paper and cardboard, glass, metals and plastics in Montreal. Besides these waste types, lightweight packaging was additionally classified as recyclable waste in Trento. For the two cities, the amount of organic waste was the sum of food and green wastes. The impacts of the COVID-19 lockdown in changing waste amount and composition were evaluated by waste variations. The variations (V_i^j , %) of any type of MSW (W_i , tons) between a COVID-19 pandemic period (j) in 2020–2021 versus the same period in 2019 were calculated using Eq. 3:

$$V_i^j(\%) = \frac{W_{\text{COVID}_i^j} - W_{2019_i}}{W_{2019_i}} \times 100\% \quad (3)$$

Results and discussion

Effects of lockdown intensity on people mobility

We studied the effect of successive lockdowns and unlocking on the amount of municipal waste during the pandemic in 2020–2021, compared to 2019, in six countries. The

mobility index represented the mobility change in visitor numbers throughout the pandemic, and the rapid variations in mobility were generally seen on weekends or holidays. Figure 1 shows that these countries have generally experienced four lockdown periods in 2020: pre-lockdown in January–February, first lockdown in February–May, unlocking in May–October, and second lockdown in November–December. However, Italy, France and USA implemented unlocking measures in January 2021, while the other three countries imposed stricter restrictions. Italy and France implemented the lockdown measures about half a month earlier than Canada and Brazil (Fig. 1).

Results show that the lockdown intensity increased sharply at the onset of the first lockdown for all countries (Fig. 1). During the first lockdown, the intensity was slightly higher, at level 5, for France and Italy, whereas the intensity of other countries was at level 4. Then, during the first unlocking, the intensity decreased more for France and Italy, to level 3, than for other countries, with few or no decrease at level 4 until 2021. The second lockdown induced again a sharp increase of lockdown intensity for France and Italy. Overall, France and Italy experienced stronger variations in lockdown intensity.

The people mobility displayed in general reversed trends versus lockdown intensity, with more amplitude for France and Italy (Fig. 1). Mobility was slightly lower in major cities such as Trento and Montreal, versus the whole countries, which possibly indicates stricter enforcement in cities versus rural areas. Pearson correlation of stringency index and people mobility shows stronger relationships (r) for France (-0.817) and Italy (-0.803) than for UK (-0.758), USA (-0.698), Brazil (-0.600) and Canada (-0.597) (Table S.7). Therefore, the lockdown was more efficient in France and Italy, which both applied a ‘rest’ period during the first unlocking. In other words, a too long period of intense locking is less effective, as clearly observed for Brazil, and to a lesser extent in USA and Canada where people mobility increased steadily despite high lockdown intensity. A possible explanation is that during prolonged lockdown, people get stressed by immobility, adapt and find a way to move. Overall, higher variations in lockdown intensity in France

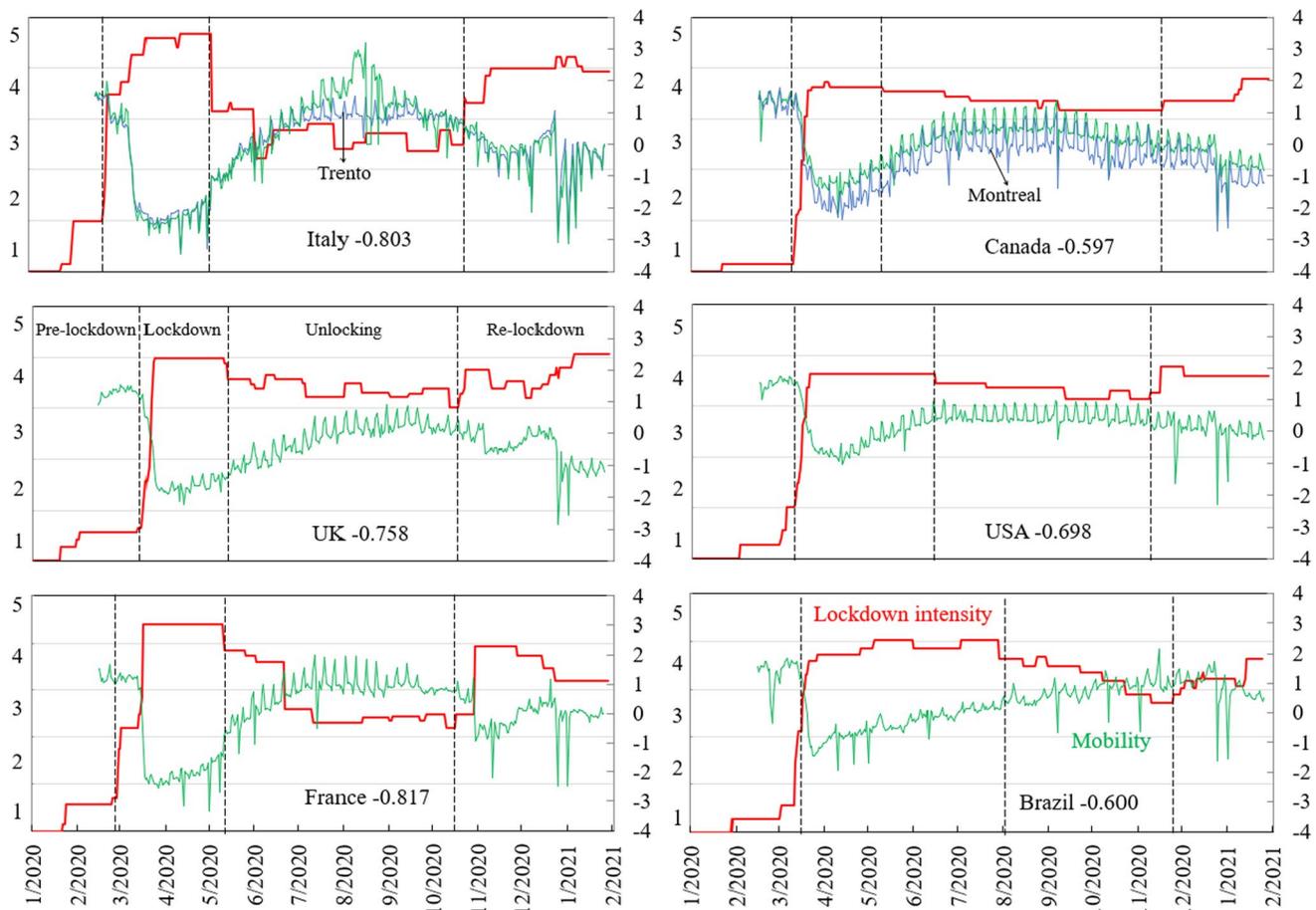


Fig. 1 Lockdown intensity and mobility index in 2020 in different cities/countries in Euro-America during the pandemic. The red lines show the lockdown intensities (I) on the primary vertical axis which are evenly classified into five levels based on the stringency index, that is, level 1, 2, 3, 4 and 5 for 0–20, 20–40, 40–60, 60–80 and 80–100, respectively. The green lines show the mobility indexes (M^I) on the secondary vertical axis based on the national mobility changes

in visitor numbers throughout the pandemic. Montreal in Canada and Trento in Italy were selected as the representative cities for America and Europe, respectively. Similarly, the blue lines show the M^I values based on the city mobility changes in visitor numbers throughout the pandemic. The black vertical dashed lines show different lockdown periods in the pandemic according to I and M^I values

and Italy were more efficient at reducing the people mobility, versus prolonged lockdowns in UK, USA, Brazil and Canada.

Waste amount dynamic during successive lockdowns

Figure 2 shows the waste variations (%) in the amount and composition of Montreal and Trento. Compared to the normal periods in 2019, significant decreases in total waste amount were observed in most of the months in 2020–2021 in Montreal (e.g., by 9.5% in May 2020) and Trento (e.g., by 13.7%, 25.3%, 14.7% from March to May 2020 and 16.5% in January 2021). For the major waste composition, both organic and recyclable wastes showed similar trends as the total waste amount, down by 8–19%. These results were observed when the national lockdown intensity is high, at

levels 4–5, and the municipal mobility index is low, ranging from –2 to –1 (Fig. 1). Moreover, waste decreases in Trento were generally larger than those in Montreal because of the higher lockdown intensity and lower mobility index in Trento. This indicates that the significant reduction of people’s movements could cause large decreases in waste amount. Notably, New York City and Stanford University communities in USA experienced significant decreases in commercial and construction wastes, nearly 50% and 60%, respectively, in March (The Conversation, 2020; WasteAdvantage, 2020). Brno’s household waste also decreased by 2.6% and 6.9% in April and May, respectively, and its commercial and industrial wastes dropped nearly 40% in June (Fan et al. 2020). UK’s residual waste decreased by about 11%, with commercial and industrial waste down by about 40% during April–June (Tolvik 2020). These results indicate that prolonged lockdowns caused larger decreases in

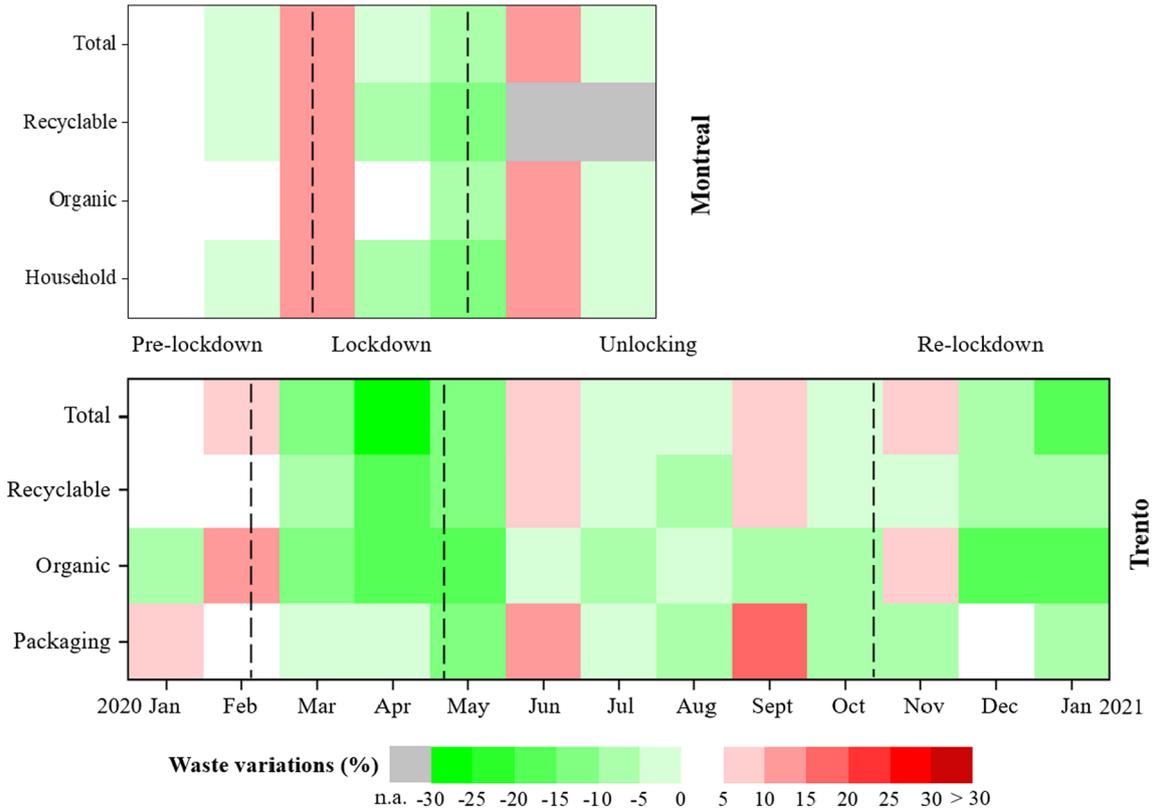


Fig. 2 Increases (red) and decreases (green) of municipal waste amount and composition in Montreal and Trento during the pandemic. The variations (V_i^j , %) of any type of waste (W_i , tons) between a COVID-19 pandemic period (j) in 2020–2021 versus the same period in 2019 were calculated using Eq. 3:

$$V_i^j(\%) = \frac{W_{COVID_i^j} - W_{2019_i^j}}{W_{2019_i^j}} \times 100\%. \text{ The red grids mean that the waste}$$

commercial and construction wastes than household waste due to the drastic reduction in business, construction and tourist activities.

There were about 12% increases in the total waste amount in both March and June for Montreal, while nearly 9% increases were all observed in February, June and September for Trento. Each type of Montreal’s waste increased by about 11% in March and June. However, Trento’s organic waste increased by 10.6% in February and its packaging waste increased by 12.1% and 16.4% in June and September, respectively (Fig. 2). Besides, February–April 2020 and November 2020–January 2021 experienced the first lockdown and second lockdown periods, respectively. Thus, waste variations in Trento showed periodic changes under re-lockdown measures as that observed since the first lockdown period (Figs. 1 and 2). In the first month of lockdowns, the panic shopping of necessary items, inappropriate cooking habits, such as overcooking, broken food supply chains, packaged take-out orders and home-delivered businesses, might result in increased food and packaging wastes (Aldaco

amount during the lockdown periods in 2020 increased compared to the normal periods in 2019, whereas the green grids mean the decreases in waste amount. The gray grids mean no data available. The black vertical dashed lines show different lockdown periods in the pandemic

et al. 2020; Jribi et al. 2020). In addition, unlocking might cause many inhabitants to return to normal food habits and produce more food waste than the average (WRAP 2020). Thus, revenge consumption might explain June’s increase in Montreal’s MSW. Besides, the transition from in-store shopping to online shopping would increase the amount of in-home recyclable packaging waste (Ikiz et al. 2021). The visitors to retail & recreation places and grocery & pharmacy stores were still much fewer than those during the normal periods, even though the lockdown intensity was reduced to level 3 (Fig. 1; COVID-19 Community Mobility Reports 2021). This means that lockdown measures influenced consumers’ behaviors during the pandemic, leading to an increase in online shopping and packaging wastes in Trento. These increases were observed in the first month of lockdowns and the second month of unlocking, likely because unlocking requires more response time. Overall, the initial implementation of lockdown or unlocking measures promoted inhabitants’ consumption, generally leading to an increase in waste amount. Moreover, consumers’ behaviors

in different lockdown periods affect variations in waste amount and composition.

Besides people's movements and consumers' behaviors, waste management affects waste amount and composition. For example, MSW was generally collected more on Mondays, Tuesdays and Thursdays than on Wednesdays and Fridays in Montreal. Therefore, the significant monthly variations in Montreal's MSW amount were likely due to more "major collection weekdays" in March and June while less in April, May and July in 2020 compared to 2019. Considering the spreading risks of contaminated wastes in recycling services, some Euro-American areas, including the six selected countries, restricted selective collections, e.g., a 35.5% reduction between March 23 and April 24 in Brazil, and recycling services, e.g., a 46% decrease in USA. Alternately, single-use plastic packaging was resurged, and recovery facilities were partially stopped in these countries. Consequently, the amount of recyclable waste generally decreased, but mixed and bulky wastes increased during March–April 2020 because of significant changes in waste management services during the early pandemic (Fan et al. 2020; Gorrasi et al. 2020; Ragazzi et al. 2020). Overall, larger variations in the waste amount in Trento were in line with higher lockdown intensity compared to those in Montreal, affected by people mobility, consumers' behaviors and waste management.

Conclusion

Our results showed the long-term effect of varying pandemic lockdowns on waste variations during different lockdown periods in some Euro-American regions during 2020–2021. Overall, the government lockdown intensity and people's movements changed with the varying lockdowns, resulting in variations in the amount and composition of MSW during the pandemic. Generally, there have been mainly four successive lockdown periods in 2020 and people mobility appears better controlled in Italy and France versus USA, Brazil, Canada, UK. We found prolonged lockdowns caused larger decreases in commercial and construction wastes than household waste due to the drastic reduction in business, construction and tourist activities. The beginning of lockdown or unlocking measures promoted inhabitants' consumption, generally leading to an increase in waste amount. Moreover, larger variations in the waste amount in Trento were in line with higher lockdown intensity compared to those in Montreal, affected by people mobility, consumers' behaviors and waste management. Notably, the inadequacies of waste management systems in the early pandemic may lead to a decrease in waste collection of recyclable waste but an increase of bulky and mixed wastes. Thus, an appropriate strategy for the whole waste management system,

including waste generation, collection, transport, recycling and disposal, should be considered to reduce waste for incineration and direct landfilling and increase waste recycling. Furthermore, the use of some new approached such as the automated waste management system through the Internet of Things can alleviate the risk of labor shortage and workers' infection. Lastly, the resurgence of single-use plastic packaging is a temporary alternative, although it may cause further microplastic pollution and affect public engagement in MSW management after the pandemic. The recovery of waste management practices and policies based on a circular economy can be a priority.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10311-021-01290-z>.

Authors' contribution Mengfan Cai conducted the study and wrote the article. Christophe Guy, Martin Héroux, Eric Lichtfouse, and Chunjiang An conceived the study and revised the article.

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Declarations

Conflict of interest This is to certify that the authors of this manuscript have no affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.

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SUPPLEMENTARY MATERIAL

The impact of successive COVID-19 lockdowns on people mobility, lockdown efficiency, and municipal solid waste

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Principal component analysis (PCA) was adopted to generate the composite mobility indexes from six variables of locations, including residential places, grocery & pharmacy stores, workplaces, parks, transit stations, and retail & recreation. The results are shown in Table S.1-S.6.

Table S.1. Correlation Matrix ^a

		Retail & recreation	Grocery & pharmacy	Parks	Transit stations	Workplaces	Residential
Correlation ^b	Retail & recreation	1.000	0.780	0.536	0.842	0.629	-0.820
	Grocery & pharmacy	0.780	1.000	0.339	0.648	0.542	-0.574
	Parks	0.536	0.339	1.000	0.308	0.091	-0.437
	Transit stations	0.842	0.648	0.308	1.000	0.803	-0.882
	Workplaces	0.629	0.542	0.091	0.803	1.000	-0.864
	Residential	-0.820	-0.574	-0.437	-0.882	-0.864	1.000

a. Determinant = 0.002; b. Significance < 0.001

Table S.2. KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.707
Bartlett's Test of Sphericity	Approx. Chi-Square	2.003×10^4
	df	15
	Sig.	0.000

Table S.3. Anti-image Matrices

		Retail & recreation	Grocery & pharmacy	Parks	Transit stations	Workplaces	Residential
	Retail & recreation	0.747^a	-0.638	-0.171	-0.424	0.356	0.401
	Grocery & pharmacy	-0.638	0.702^a	-0.121	-0.005	-0.397	-0.413
Anti-image	Parks	-0.171	-0.121	0.503^a	0.258	0.535	0.539
Correlation	Transit stations	-0.424	-0.005	0.258	0.882^a	-0.125	0.303
	Workplaces	0.356	-0.397	0.535	-0.125	0.635^a	0.784
	Residential	0.401	-0.413	0.539	0.303	0.784	0.672^a

a. Measures of Sampling Adequacy (MSA)

Table S.4. Communalities ^a

	Initial	Extraction
Retail & recreation	1.000	0.871
Grocery & pharmacy	1.000	0.618
Parks	1.000	0.237
Transit stations	1.000	0.866
Workplaces	1.000	0.685
Residential	1.000	0.882

a. Extraction Method: Principal Component Analysis.

Table S.5. Component Matrix ^a

	Component ^b
	1
Retail & recreation	-0.939
Grocery & pharmacy	0.933
Parks	0.930
Transit stations	0.828
Workplaces	0.786
Residential	0.487

a. Extraction Method: Principal Component Analysis. b. 1 components extracted.

Table S.6. Component Score Coefficient Matrix ^a

	Component ^b
	1
Retail & recreation	0.224
Grocery & pharmacy	0.189
Parks	0.117
Transit stations	0.224
Workplaces	0.199
Residential	-0.226

a. Extraction Method: Principal Component Analysis. b. Component Scores.

Table S.7. Pearson correlation (r) of stringency index (SI) and mobility index (M^i).

Country / City	Italy	UK	France	Canada	USA	Brazil	Trento	Montreal
Correlation (r)	-0.803**	-0.758**	-0.817**	-0.597**	-0.698**	-0.600**	-0.770**	-0.664**
Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Notes: *. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed)