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RESEARCH ARTICLE

COVID-19 lockdown and municipal solid waste: evidence from the discarding records of 252 communities in China

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Abstract
This study investigates the impacts of the COVID-19 lockdown on municipal solid waste (MSW). Based on a unique data set of daily discarding records of 252 communities in Beijing, China, we conduct a difference-in-differences estimation and find that the total daily MSW decreased by 134.16 kg in a community, which is equivalent to at least 0.22 kg per household per day, and the average weight of MSW per package decreased by 56.8 per cent after the COVID-19 lockdown. We consider a series of potential mechanisms, such as MSW hoarding, shifts in discarding time, and fear of going out, and find the most support for consumption pattern shifts with reduced consumption. We then discuss the effect of the lockdown on the reduction of MSW generation because of the strict restriction of consumption. We also conduct various heterogeneity analyses. Our results present clear implications for municipal waste management by highlighting the effect of the lockdown on the generation of MSW and the underlying consumption mechanism.

Keywords: China; COVID-19; lockdown; municipal solid waste (MSW)

JEL Classification: Q52; Q58

1. Introduction

Solid waste is increasingly recognized as a serious worldwide environmental concern. Anecdotal evidence documents that a collapse of a waste site killed 69 people in Shenzhen, one of the most advanced cities in China, in 2015 (Yang *et al*., 2016). Municipal solid waste (MSW) directly causes negative externalities to both health and the environment. Residential exposure to the waste site is well-established to be significantly associated with asthma, tuberculosis, diabetes and depression (Tomita *et al*., 2020). The combustion and landfill of MSW lead to air pollution (Muller *et al*., 2011) and water pollution (Yu *et al*., 2020), respectively. MSW also causes marine pollution and even flows into our food chain (Jambeck *et al*., 2015).

To reduce the negative impact of MSW, the widely recognized 3Rs principle calls on the public to reduce, reuse and recycle, which emphasizes reducing the impact of waste at the source. It suggests the crucial role of consumption patterns in determining the generation of MSW. However, probably owing to the difficulty of identification, the causal effect of consumption pattern changes on the reduction of MSW generation has not undergone a thorough evaluation. Accordingly, we fill the gap in this study.

This paper approaches this issue by examining the effect of the COVID-19 lockdown, a sound natural experiment that changes the patterns of consumption, on MSW generations. In particular, the outbreak of the COVID-19 pandemic and the lockdown policy implemented to control the disease has had a profound influence on the world's economy. Recent literature has documented its impact.[1] As an endless activity of urban metabolism, the generation, discarding, and disposal of MSW[2] should have been largely influenced. Surprisingly, studies have scarcely examined the effect of the COVID-19 lockdown on MSW.

In this article, we quantify the reduction of MSW generation by eliminating the types of consumption that create a large amount of waste, such as takeaway, express delivery, and over-packaging. With unique data from the discarding records of 252 communities in Beijing, we conduct a difference-in-differences (DiD) model following Abrams (2021). The daily total MSW decreased by 134.16 kg in a community, which is equivalent to at least 0.22 kg per household per day, and the average weight of MSW per package decreased by 56.8 per cent.

One concern of estimating the COVID-19 lockdown impact in China is that the Lunar New Year (January 25, 2020) was very close to the beginning of the lockdown (January 23, 2020), which may bias our estimation. Thus, we further conduct a DiD model based on the lunar calendar to address this issue, and the results suggest that the decrease in MSW remains significant after excluding the New Year effect. We also conduct an event study analysis. All the results verify the robustness of our findings.

Some analyses of the scientific literature show that the impact of the COVID-19 lockdown on MSW is ambiguous. Fan *et al*. (2021) find that the household waste amount decreased by about 23 per cent in Shanghai, while waste increased by 1 per cent in Brno, Czech Republic, and increased by 3 per cent in Singapore. Leal Filho *et al*. (2021) conducted a survey in several countries[3] other than China and find that plastic packaging waste increased by 53 per cent due to the increase in takeout due to travel restrictions. Therefore, it is necessary to discuss the reasons and mechanisms behind the reduction of MSW during the lockdown in China.

We explore the underlying mechanism of the MSW decrease. We first consider the ways that the reduction effect could arise from hoarding behavior and shifts of discarding time. The lockdown restricted mobility, prohibited public gatherings, shut down schools

[1] A series of recent literature has estimated the effect of the COVID-19 lockdown on various outcomes, such as the spread of COVID-19 (Fang *et al*., 2020), air pollution (He *et al*., 2020; Brodeur *et al*., 2021; Dang and Trinh, 2021), house prices (Irwin and Livy, 2021), students' academic performance (Bilen and Matros, 2021), and crime (Abrams, 2021).

[2] Waste generation in this paper refers to the behavior of people consuming and using commodities to generate garbage. Waste discarding in this paper refers to the behavior of households dumping the generated trash into the dump in the community. The disposal of garbage includes terminal treatment processes such as sorting, incineration or landfill.

[3] The countries surveyed include: Portugal, Italy, Germany, Brazil, Estonia, United States, Australia, Canada, Singapore, United Kingdom, Denmark, Spain, Poland, Finland, Bangladesh, Argentina, Chile, Ireland, New Zealand, Japan, Malaysia, Indonesia and Vietnam.

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and workplaces, and also caused panic. We suppose that the generation of MSW has not decreased but only that the households have changed their discarding frequency. The detailed records allow us to rule out the hypothesis and we present evidence that hoarding behavior is unlikely to explain our results. In particular, the MSW weight of each discard significantly decreased after the lockdown, which is the opposite of the hoarding effect. The decreasing effect of MSW is robust even when we control the information on local and national COVID cases in our model and the outbreak of local COVID cases has an insignificant effect on MSW discarding, which indicates that 'the fear of going out effect' could not explain our findings. Furthermore, we find that both the total weight of MSW and the average weight of MSW per package do not return to the previous level after the lockdown policy is lifted. This finding suggests that the households do not shift the discarding time but reduce the generation of MSW in the long run.

We next investigate the reduction of the generation of MSW as consumption is restricted. We conduct a placebo test of the restriction of offline activities based on the second round of the COVID-19 outbreak and the corresponding control policy in Beijing. The Chinese government has taken prompt measures, such as school closing and restrictions on public gatherings to control the new round of epidemic. Differently from the first lockdown, the epidemic prevention measures in June did not strictly prohibit commercial activities. We conduct an event study analysis and find that MSW did not significantly decrease in June. This result suggests that the shutdown of consumption after the lockdown reduced the generation of MSW. Compared to the well-documented increase in MSW induced by epidemic prevention policies in countries other than China (Fan *et al.*, 2021; Leal Filho *et al.*, 2021), we emphasize that the strict restriction of consumption, such as food take out and express delivery, significantly reduced the generation of MSW in China.

Our finding contributes to the emerging literature estimating the impact of the COVID-19 lockdown. Fang *et al.* (2020) evaluate the effect of the lockdown policy and the spread of the COVID-19 pandemic in China. In the field of environmental economics, several existing studies examine the effect of lockdown policy on the improvement of air pollution (He *et al.*, 2020; Liu *et al.*, 2020; Dang and Trinh, 2021). Our paper supplements the examination of environmental effects of the lockdown. Considering that the generation of MSW comes from consumption which has been widely halted during the lockdown, estimating the reduction of MSW is intuitive.

The current study also fills the void in the literature about MSW. Valente and Bueno (2019) evaluate the effect of the Unit Pricing System on the reduction of household generation in Italy. Ek and Miliute-Plepiene (2018) find that the Swedish food collection policy has had a positive spillover effect and has promoted the reduction of packaging waste. Akbulut-Yuksel and Boulatoff (2021) explore the effect of the green nudge policy on households' recycling and MSW from a behavioral perspective. Taylor (2020) evaluates the time cost of bag policy to reduce MSW. All these studies are evaluating the cost and benefits of policy objectives to reduce waste. Our work is different from theirs in terms of utilizing the natural experiment of the COVID-19 lockdown to estimate the reduction of MSW. We are the first study to provide evidence of the effect of consumption pattern change induced by exogenous shock on the reduction of MSW generation.

Our finding also offers clear implications for waste management and the post-pandemic world. In early 2018, the government of China banned the import of several types of waste, which has largely affected the recycling industries worldwide, as China has been the largest importer of waste plastics (Brooks *et al.*, 2018). China itself produces a lot of waste. Zhou *et al.* (2020) find that the rapid growth of the express delivery and takeaway market generated 323 kilotons of waste in 2018. Therefore, the study of MSW in China has practical significance for the entire international recycling industry. This paper provides an estimation of MSW generated by ordinary residents in China and estimates the reduction of MSW generation. We also call on the public to reduce unnecessary consumption and put the 3Rs principles into practice, to mitigate the negative welfare impact of MSW at the source.

2. Data and empirical strategy

2.1 Data

The data used in our analysis contain information about MSW discarded every day. We obtained the data from a waste collection company,[4] which serves 252 communities in Changping, a district in northwest Beijing. The data contain detailed discarding records of these communities from 2019 to 2020, including the weight, time and place of discarding. Since the accumulation of domestic waste in communities would cause great problems, the garbage collection company was still in normal operation during the period of the lockdown. This ensured that we can still obtain data on waste discarded during the lockdown. Owing to service limitations, the company only provides garbage collection services other than organic waste. In other words, our sample only includes refuse and recyclable solid wastes.

We show the spatial dispersion of our sample communities in figure 1 using the geographical information of the communities. Changping District has a resident population of 2.166 million. Owing to the large areas of mountains and parks in Changping District, our sample communities are relatively concentrated as shown in online appendix figure A1.

We subsequently merge the data on municipal waste with the COVID-19 lockdown policy data of China. We refer to He *et al.* (2020) and Dang and Trinh (2021) and collect the lockdown information from Oxford University's COVID-19 Government Response Tracker (OxCGRT). On January 23, 2020 China began to take strict measures to control the COVID-19 epidemic, including store closing, suspension of work and schools, stay-at-home requirements, and traffic control to restrict public gatherings and mobility (Hale *et al.*, 2020). Unlike many other countries, China's lockdown was implemented simultaneously. However, food materials purchases and municipal waste disposal services necessary for life were not restricted.

According to the government announcements and news collected by OxCGRT, Beijing implemented a lockdown policy similar to the one in Wuhan and canceled the annual grand event of celebrating the Spring Festival, closed major scenic spots, and advocated that citizens reduce mobility on January 23. In the following two days, Beijing suspended the long-distance bus service. Furthermore, China Railway canceled hundreds of trains in the following week, and Beijing required people traveling from Hubei Province to be isolated. Overall, while the measures in Beijing were not as strict as those in Wuhan, it also implemented similar measures to restrict mobility.[5] Figure A2

[4]The garbage collection company provides exclusive services for garbage other than organic garbage in the community. The company only deals with the garbage generated by households in the communities, not including the garbage generated by stores.

[5]Also see news about the COVID-19 pandemic in China available at https://global-monitoring.com/gm/page/events/epidemic-0001905.3QnJ7K8JC559.html?lang{\mathsurround=\opskip$=$}en.

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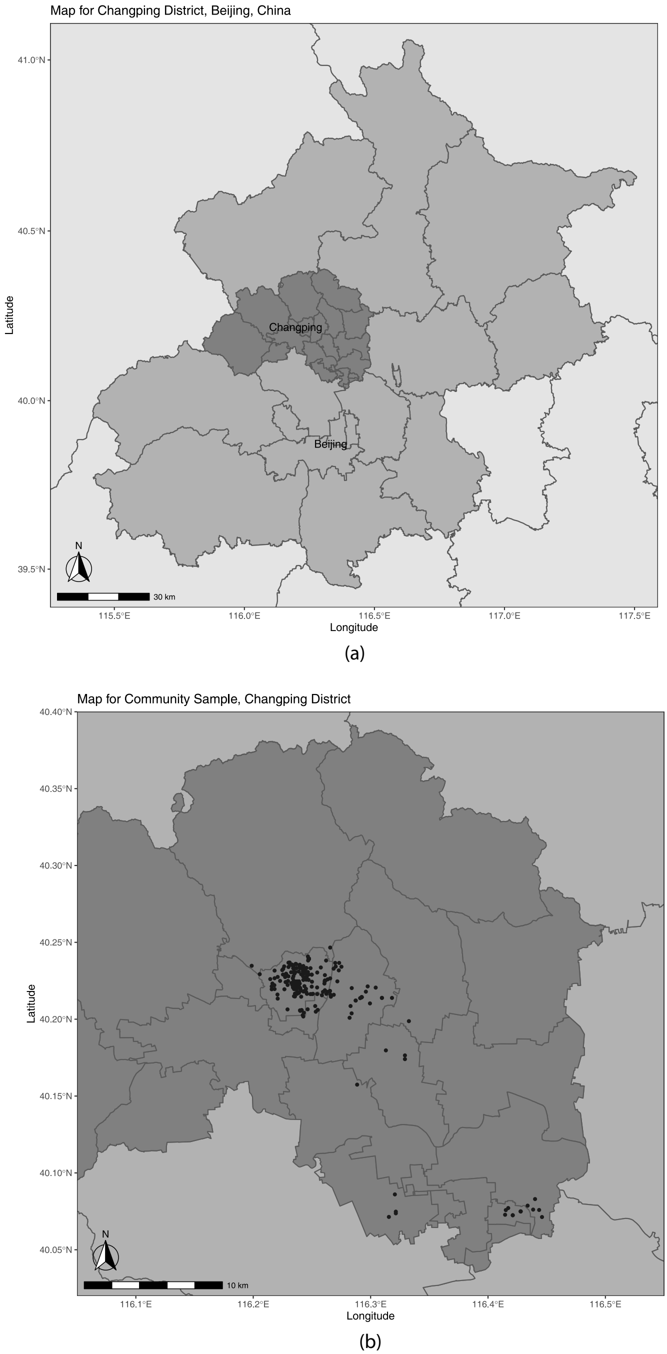

Figure 1. Map of Changping District, Beijing, China.
Notes: Panel (a) shows the relative location of Changping District in Beijing. Panel (b) shows the geographical distribution of sample communities.

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(online appendix) plots the newly confirmed cases and the total number of confirmed cases in Beijing from January to May, which shows that there were a large number of cases in Beijing in January.

We add to this data information about local weather and the characteristic of each community. The weather data were collected from the China Meteorological Data website[6] and contain daily temperature and wind speed.[7] Temperature is measured in centigrade, and wind speed is measured in meters per second. We manually collected the community characteristics from a real estate transaction website called Lianjia.com (at https://bj.lianjia.com/ershoufang/) to analyze the community heterogeneity. Data were collected on average house price, construction year, the total number of households, and property service information.

2.2 Empirical strategy

Most empirical work estimating the impact of the COVID-19 lockdown is built on Regression Discontinuity Design (RDD), such as that of Dang and Trinh (2021) and Takaku and Yokoyama (2021). However, China's 2020 Lunar New Year was on January 25, which is very close to the imposition of the COVID-19 lockdown (January 23, 2020) and may thus become a confounding factor affecting MSW generation. Before the Lunar New Year, Chinese families have the custom of cleaning. Even if China had not implemented the lockdown policy, more solid waste before the Lunar New Year would have been anticipated than after. The RDD method directly compares the weight of waste discarded in each community before and after the lockdown, and the results will be biased by the New Year's cleaning customs.

To overcome the bias induced by the Chinese Lunar New Year., we refer to He *et al.* (2020), Fu and Gu (2017), and Abrams (2021) and conduct a DiD regression where the comparison group for each community is itself in 2019:

$$MSW_{cdy} = \alpha + \beta_1 \text{treat}_y \times \text{After}_{cd} + \beta_2 \text{After}_{cd} + \beta_3 \text{treat}_y + \beta X_{dy} + \pi_d + \mu_c + \varepsilon_{cdy}, \tag{1}$$

where MSW_{cdy} is the weight of MSW thrown away in c community on day d in year y. treat_y equals 1 if the year is 2020; otherwise equals 0. After_{cd} is 1 on the solar calendar day when the lockdown policy is implemented regardless of year. β_1 is the parameter of interest. X_{dy} is a vector of observed time-varying control variables, such as temperature and wind speed. Since the severe cold and bad weather may affect people's decision regarding waste discarding at the same time, we added weather conditions to the control variables.[8] π_d and μ_c respectively denote the weekday and community fixed effects. We estimate equation (1) with a window of one month before and after the lockdown.[9]

[6] Data from the China Meteorological Data (http://data.cma.cn/) include the record of the only weather monitoring station in Changping District. Since the sample communities are located within about 50 km of the core of Changping District, we believe that the record of the monitoring station can accurately represent the weather conditions.

[7] We did not collect the precipitation variable because Beijing, with a temperate continental climate, has no precipitation record from January to February in 2020.

[8] Since there was no precipitation in Beijing in the event window, we did not add precipitation as the control variable.

[9] In the baseline regression, the time window of the treatment group is from December 23, 2019 to February 23, 2020. The time window of the control group based on the solar calendar is from December 23, 2018

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Considering the bias induced by the Chinese New Year cleanup custom, we conduct a robustness check by using the corresponding lunar calendar of 2019 as the control group. Specifically, the lockdown day (January 23, 2020) happened two days before the Chinese New Year and corresponds to January 23, 2019, in the solar month. However, in the lunar calendar, the lockdown day corresponds to February 3, 2019, which is also two days before the Lunar New Year in 2019. After_{cd} is 1 after February 3 in 2019 and after January 23 in 2020 for regression based on the lunar calendar.

We also conducted an event study of the treatment and control groups to ensure the parallel trend in 2019 and 2020 before lockdown day. The basic event study model is given by

$$MSW_{cdy} = \alpha + \Sigma_{j=-9}^{10}(\beta_{1j}\text{treat}_y \times \text{day}_j) + \beta_2\text{After}_{cd} + \beta_3\text{treat}_y + \beta X_{dy} + \pi_d + \mu_c + \varepsilon_{cdy}, \quad (2)$$

where MSW_{cdy} is the weight of MSW, and treat_y is 1 if the year is 2020. day_j is a dummy for the day on which time j is before or after the calendar date when the lockdown policy is implemented regardless of year. Similar to equation (1), the event study analysis also includes the weather controls and year, weekday and community fixed effects.

Table 1 reports the summary statistics of all the variables. The average number of households in the sample community is 1,186. The average daily waste weight of each community is 156.3 kg and 125.6 kg during January and February of 2019 and 2020, respectively. One possible reason is that many people in Beijing return to their hometown during the Spring Festival and the waste weight counted in our sample does not include organic waste, the average daily waste weight of each community is relatively small.

3. Empirical results

Table 2 reports the results of estimating equation (1). Panel A reports the change in the total daily weight of MSW. Standard errors are clustered at the community level and reported in parentheses. The coefficient of the cross term in column (1) is 155.507 and is significant at the level of 1 per cent, which indicates that the total daily weight of MSW discarding fell rapidly, broadly, and substantially, that is, 155.507 kg for every community overall. Considering that the MSW discarding behavior may be influenced by time-varying variables, we further add weather controls in column (2). The coefficient only increases by 1.772 and remains significant at the level of 1 per cent. The weather control of temperature is positive and significant, which indicates that the warmer the weather, the more people go out to discard waste in winter.

As discussed earlier, one concern is that the Chinese Lunar New Year, which is close to the lockdown day, may bias our estimation. The custom of cleanup may increase the MSW discarded before New Year's Day and also before the lockdown day. We investigate whether this scenario is the case by estimating the equation based on the lunar calendar. The coefficient of a cross term is 129.478 and remains significant. We further add weather controls. The coefficient turns to 134.157 and is statistically significant. This finding indicates that the MSW decreased after the Lunar New Year, but the effect of

to February 23, 2020, while the time window of the control group based on the lunar calendar is from January 3, 2019 to March 3, 2019.

Table 1. Summary statistics

	Jan–Feb of 2019, 2020				Jan–Feb 2019				Jan–Feb 2020				*t*-test
Variables	Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max	statistics
MSW (kg)	127.04	210.764	0.10	2,820.50	156.30	179.503	1.00	1,743.35	125.64	212.319	0.10	2,820.50	33.128
ln(MSW)	3.82	1.562	−2.30	7.94	4.39	1.285	0.00	7.46	3.79	1.569	−2.30	7.94	0.650
MSW per pack. (kg)	7.97	9.227	0.10	256.00	8.85	6.794	1.00	69.00	7.90	9.308	0.10	256.00	0.995
ln(MSW per pack.)	1.73	0.816	−2.30	5.55	1.94	0.701	0.00	4.23	1.72	0.817	−2.30	5.55	0.231
Temperature max (°C)	5.12	3.656	−4.00	14.00	5.93	4.490	−4.00	14.00	5.00	3.510	−4.00	12.00	0.916
Temperature min (°C)	−6.31	3.298	−15.00	2.50	−7.01	3.555	−15.00	−1.00	−6.36	3.303	−15.00	2.50	−0.795
Wind Speed (m/s)	23.76	11.810	9.58	73.33	27.50	12.146	9.58	62.92	23.64	11.821	9.58	73.33	4.238
COVID case in Changping	7.98	10.962											
COVID cases in Beijing	114.65	161.866											
COVID cases in China	8.83	15.210											
House price (¥)	35,521.25	5,077.254											
Construction year	1,995.51	10.167											
Property service dummy	0.62	0.484											
Property fee (¥/m2·month)	1.24	0.694											
Household	1,186.40	1,244.255											

Notes: The *t*-test statistics in the last column test whether the means of a variable in the 2019 and 2020 periods are equal.

Table 2. Response of municipal solid waste to COVID-19 lockdown

	(1)	(2)	(3)	(4)
	Based on the solar calendar		Based on the lunar calendar	
Panel A: Response of total MSW weight to COVID-19 lockdown				
Treat × after	−155.507 (21.255)	−153.735 (21.035)	−129.478 (21.678)	−134.157 (21.526)
After	15.902 (15.698)	−3.260 (15.659)	−10.127 (18.052)	−23.368 (18.318)
Temperature max		2.147 (0.926)		2.217 (0.954)
Temperature min		4.021 (0.930)		4.131 (0.905)
Wind speed		0.791 (0.262)		0.787 (0.262)
Constant	−105.029 (38.860)	−164.288 (44.072)	−90.037 (43.127)	−154.711 (47.753)
Weekday FE	Yes	Yes	Yes	Yes
Community FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	6,421	6,421	6,421	6,421
r^2	0.359	0.366	0.359	0.366
Panel B: Response of log MSW weight to COVID-19 lockdown				
Treat × after	−1.520 (0.150)	−1.509 (0.149)	−1.374 (0.075)	−1.400 (0.074)
After	0.001 (0.107)	−0.113 (0.111)	−0.145 (0.068)	−0.225 (0.070)
After	0.001 (0.107)	−0.113 (0.111)	−0.145 (0.068)	−0.225 (0.070)
Temperature max		0.021 (0.005)		0.021 (0.004)
Temperature min		0.016 (0.005)		0.017 (0.005)
Wind speed		0.005 (0.001)		0.005 (0.001)
Constant	4.750 (0.339)	1.682 (0.359)	4.818 (0.096)	1.721 (0.134)
Weekday FE	Yes	Yes	Yes	Yes
Community FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	6,420	6,420	6,420	6,420
r^2	0.632	0.636	0.632	0.636

Notes: This table shows the baseline results of the effects of the COVID-19 lockdown on the weight of municipal solid waste (MSW). Standard errors are clustered at the community level and are reported in parentheses.

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lockdown remains.[10] To prevent our results from being driven by a small number of outliers, we take the logarithm of the total weight of MSW for the robustness test. Panel B reports the change in log MSW weight. All the coefficients remain significantly negative. Overall, our findings suggest that MSW decreased in response to the COVID-19 lockdown policy.

To visually assess the dynamic change in the MSW before and after the lockdown, we estimate an event study specification with a full set of control variables and community and time fixed effects and a series of event time indicators. The event time indicators range from -9 to $+10$ before and after the lockdown day. We omit the -10 day in the event window to avoid complete collinearity. The reference group is 10 days before the lockdown window.

Figure 2 plots the results. Panel (a) reports the estimation of equation (2) based on the solar calendar, and panel (b) is based on the lunar calendar. Standard errors are clustered at the community level. The results are consistent with our previous finding that MSW is significantly lower after the lockdown date. The coefficients of the pre-event window are about -0.048 to 0.130 but the coefficient for the pre-event window is about -0.601 to -0.849, indicating a sharp decline after the lockdown. The daily MSW weight is relatively stable from 9 days before up to the lockdown. We find that MSW decreased sharply one day before the implementation of the lockdown policy, which is plausible because the announcement of lockdown was reported on the day before the lockdown day. The daily MSW weight remains low for 10 days following the lockdown policy. The direction and magnitude of the results estimated by the event study specification are consistent with those in the DiD model, suggesting that the lockdown policy significantly decreased MSW.

4. Potential mechanism

The lockdown policy to control the outbreak of the COVID-19 pandemic implemented a series of measures, which limited public gatherings, restricted population mobility, and closed offices and schools. We have established the causal relationship between the lockdown policy and MSW. Thus, what is the potential mechanism of the impact on MSW? Does the lockdown policy only reduce the amount of MSW thrown away or does it reduce the amount of MSW generated? We next consider several potential explanations for the lockdown effects that do not reduce the amount of MSW generated.

4.1 Effects of MSW hoarding

One possible explanation for the previous finding is hoarding behavior. The lockdown policy may not directly influence the generation of MSW; instead, people merely hoard garbage at home and reduce the frequency of waste discarding to reduce the risk of

[10] We also analyzed the waste discarded per household and calculated MSW per household using the number of houses owned by the community and repeated the regression as the baseline analysis. Table A1 in the online appendix reports the results and the coefficients of the interactions are still significant and negative. We find that lockdown reduces the MSW generated by a typical household by about 0.22 kg. Considering that the daily non-organic waste generated by each household is about 0.34 kg, this finding is economically significant. In addition, considering that the actual occupancy rate is not more than 100 per cent, our estimation of the change in MSW per household is biased towards zero, which is at least a lower bound.

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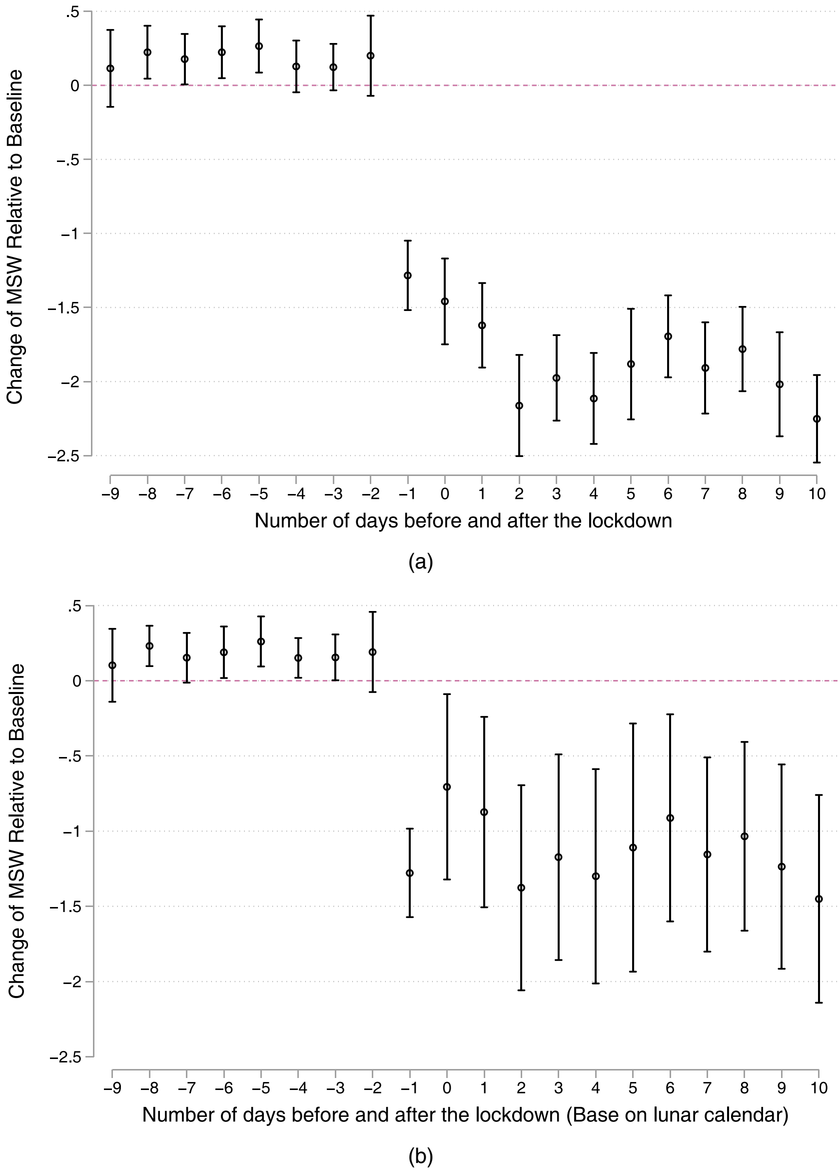

Figure 2. Event study analysis: total MSW weight.

Notes: This figure reports the effects of the COVID-19 lockdown on the total weight of MSW and 95 per cent confidence intervals for the period from 9 days before to 10 days after the lockdown. Panel (a) reports the effect measured by the solar month model and panel (b) reports the results of the lunar month model. All models also include weather controls, community dummy, weekday dummy, and year dummy. The reference group is 10 days prior to the lockdown window. Standard errors are clustered at the community level.

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Table 3. Response of MSW per package to COVID-19 lockdown

	(1)	(2)	(3)	(4)
	Based on the solar calendar		Based on the lunar calendar	
Panel A: Response of MSW per package to COVID-19 lockdown				
Treat × after	−2.849 (0.710)	−2.807 (0.707)	−2.893 (0.773)	−2.994 (0.753)
Controls	Yes	Yes	Yes	Yes
Weekday FE	Yes	Yes	Yes	Yes
Community FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	6,421	6,421	6,421	6,421
r^2	0.398	0.400	0.398	0.400
Panel B: Response of log MSW per package to COVID-19 lockdown				
Treat × after	−0.557 (0.077)	−0.552 (0.077)	−0.556 (0.078)	−0.568 (0.076)
Controls	Yes	Yes	Yes	Yes
Weekday FE	Yes	Yes	Yes	Yes
Community FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	6,420	6,420	6,420	6,420
r^2	0.603	0.606	0.603	0.606

Notes: This table shows the effects of the COVID-19 lockdown on the average weight per package of MSW. Standard errors are clustered at the community level and are reported in parentheses.

COVID-19 exposure.[11] If this mechanism works, the total amount of MSW generated has not decreased, but the frequency of people throwing garbage has decreased. Our sample communities are all buildings and apartments, implying that people may have to throw away a large amount of garbage every time due to the difficulty of hoarding garbage for a long time in their homes.

To access the MSW hoarding mechanism, we estimate the effect of lockdown on the average weight of MSW per package[12] with equation (1). The weight of each package of waste refers to the weight of the garbage discarded at one time. If there is a hoarding effect, the average weight of each discard will increase. If the amount of waste generation reduces, the weight of waste discarded at one time will reduce. We expect the coefficient of the cross-term to be significantly positive, which suggests people hoarding garbage and a decrease in the frequency of discarding.

Table 3 reports the effect of lockdown on the average weight of MSW per package. The coefficient of the cross term is −2.89 and is statistically significant at the level of 1 per cent. Even when we add the weather controls and change the control group based

[11]Unlike those buildings where household garbage disposal pipes are installed, families in our sample communities have to go out to discard garbage.

[12]Our sample records the weight each time that garbage that is thrown away; thus, even if more than one pack of garbage is discarded at a time, it is still counted as one pack.

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on the lunar calendar, the results remain robust. We further estimate the effect of log MSW per package and find that the lockdown reduces the average weight of MSW per package by 55.2 per cent. These results are suggestive of the fact that the decrease in MSW after the lockdown occurred not because they hoarded garbage and reduced the frequency of discarding, but because less waste seems to have been generated.

We also conduct a time-event analysis of the average MSW per package. Figure 3 plots the results specifically based on solar and lunar calendars, which confirm the finding with a DiD model. The average MSW per package is significantly lower after the lockdown, which confirms that the hoarding effect could not explain our previous findings. Instead, the significant decrease in the average MSW per package suggests that the generation of MSW decreased after the lockdown.

4.2 Shifts of discard timing

Another alternative mechanism that would explain our finding is that the household shifted the time of discarding garbage. First, the severity of the virus may have affected the decision-making of discarding. Specifically, households delayed the time of discarding in the short run after obtaining the information on COVID-19 cases. The COVID-19 cases may also endogenously correlate with the lockdown policy and bias our estimation. Second, at the other extreme, households delayed the time of discarding until the lockdown policy was lifted in April. If the long-term shift effect is established, we will see that the amount of MSW after the lifting of the lockdown will exceed the level the day prior to it.

To test the short-term shifts in MSW discarding due to the information effects of COVID-19 cases, we refer to Brodeur *et al.* (2021) and include the lag variables of the new cases in Changping District, Beijing, and the entire country in equation (1). Table 3 reports the coefficients of the regression. Panel A reports the change in the total MSW, and panel B reports the effect of the average MSW. All the coefficients of the interaction are significantly negative. The coefficient based on the lunar calendar is −163.355 which is even lower than that in the baseline result (−134.157). This result makes sense, if the information on new cases prevents discarding, then we will see the gap in MSW before and after the lockdown widen when controlling the case information. Thus, our finding of the decrease in MSW is robust and is not driven by short-term shifts (table 4).

We next address the extreme situation that households shifted the time of discarding in a relatively long period and discarded all the garbage generated after the end of lockdown. We expect that the MSW will increase to a level higher than that before the lockdown in April. Therefore, we extend the post-lockdown window in the event study specification to 70 days after the lockdown, i.e., to April 2, when the lockdown policy was relaxed. The associated equation is

$$MSW_{cdy} = \alpha + \Sigma_{j=-9}^{70}(\beta_{1j}\text{treat}_y \times \text{day}_j) + \beta_2\text{After}_{cd} + \beta_3\text{treat}_y + \beta X_{dy} + \pi_d + \mu_c + \varepsilon_{cdy}. \tag{3}$$

Figures 4 and 5 report the long-run event study analysis of the total MSW and average MSW per package, respectively. Both total MSW and average MSW decreased dramatically at the beginning of the lockdown day and then increased slightly after approximately 20 days. MSW remained relatively stable for nearly 50 days, and the MSW weight after the opening in April did not increase to the level before the lockdown. We refer to the model based on the lunar month, but the result stays robust. These findings refute the hypothesis that households shifted the MSW discarding in the

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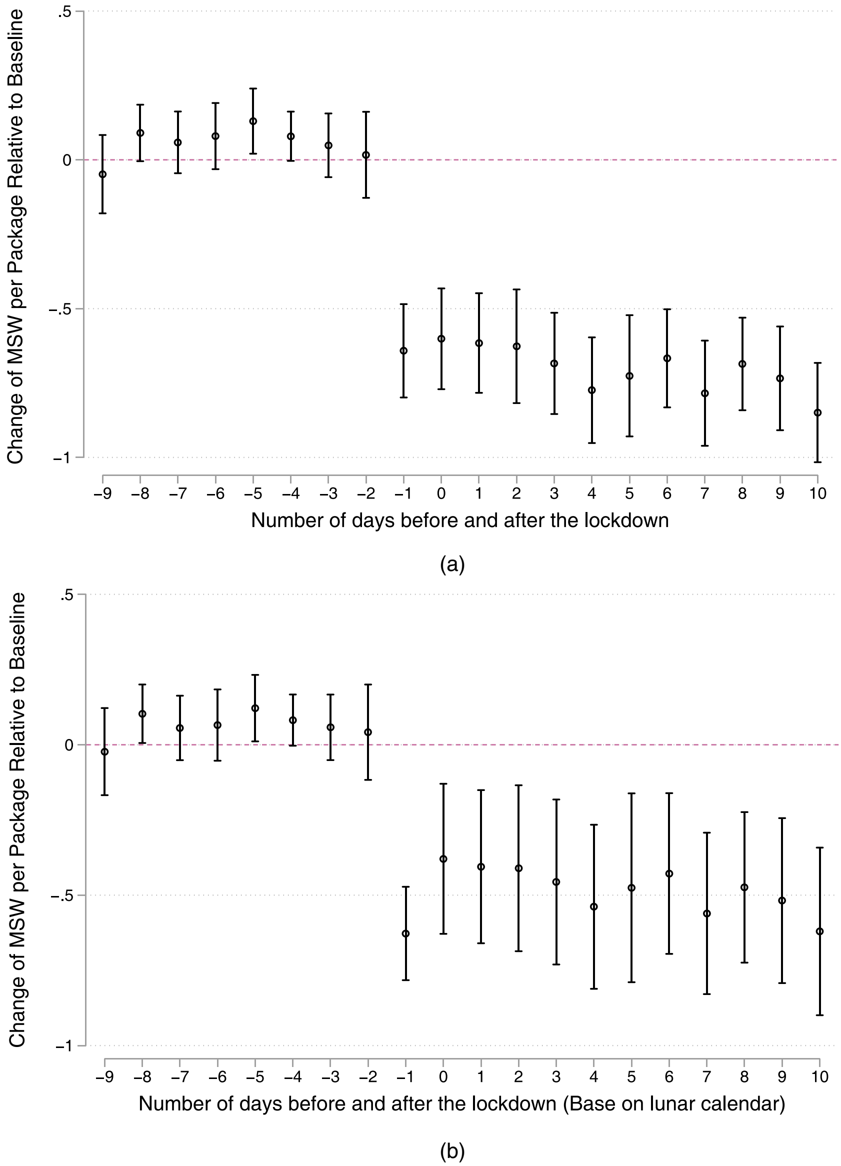

Figure 3. Event study analysis: average MSW weight per package.
Notes: This figure reports the effects of the COVID-19 lockdown on the average weight of MSW per package and 95 per cent confidence intervals for the period from 9 days before to 10 days after the lockdown. Panel (a) reports the effect measured by the solar month model and panel (b) reports the results of the lunar month model. All models also include weather controls, community dummy, weekday dummy, and year dummy. The reference group is 10 days prior to the lockdown window. Standard errors are clustered at the community level.

long run. Instead, both the total MSW weight and average MSW weight remain low after 70 days of the lockdown, suggesting that the lockdown decreased the generation of MSW.

Table 4. Robustness check: MSW response considering COVID cases

	(1)	(2)	(3)	(4)
	Based on the solar calendar		Based on the lunar calendar	
	MSW	ln(MSW)	MSW	ln(MSW)
Panel A: Response of MSW to COVID-19 lockdown				
Treat × after	−190.122 (23.677)	−1.612 (0.168)	−163.355 (24.669)	−1.464 (0.165)
After	17.031 (16.213)	0.002 (0.116)	−10.559 (19.639)	−0.150 (0.122)
Temperature max	1.122 (0.985)	0.014 (0.005)	1.266 (1.023)	0.015 (0.005)
Temperature min	−1.333 (0.923)	−0.013 (0.005)	−0.997 (0.944)	−0.012 (0.005)
Wind speed	0.282 (0.246)	0.002 (0.001)	0.293 (0.244)	0.002 (0.001)
COVID cases in Changping	0.146 (2.193)	0.011 (0.011)	0.139 (2.194)	0.011 (0.011)
COVID cases in Beijing	−0.170 (0.114)	−0.002 (0.001)	−0.163 (0.116)	−0.002 (0.001)
COVID cases in China	3.686 (0.663)	0.024 (0.004)	3.577 (0.676)	0.024 (0.004)
Constant	−199.476 (44.920)	4.271 (0.345)	−182.073 (48.348)	4.347 (0.342)
Weekday FE	Yes	Yes	Yes	Yes
Community FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	6,421	6,420	6,421	6,420
r^2	0.377	0.643	0.377	0.643
Panel B: Response of MSW per package to COVID-19 lockdown				
	MSW per package	ln(MSW per package)	MSW per package	ln(MSW per package)
Treat × after	−3.620 (0.860)	−0.615 (0.085)	−3.652 (0.898)	−0.610 (0.084)
After	0.406 (0.637)	−0.002 (0.063)	0.437 (0.685)	−0.007 (0.062)
Temperature max	0.001 (0.032)	0.001 (0.002)	0.001 (0.032)	0.001 (0.002)
Temperature min	−0.004 (0.034)	−0.005 (0.002)	−0.002 (0.033)	−0.005 (0.002)
Wind speed	−0.001 (0.009)	0.000 (0.001)	−0.001 (0.009)	0.000 (0.001)
COVID cases in Changping	0.001 (0.097)	0.003 (0.006)	0.001 (0.097)	0.003 (0.006)

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Table 4. *Continued.*

	(1)	(2)	(3)	(4)
	Based on the solar calendar		Based on the lunar calendar	
	MSW	ln(MSW)	MSW	ln(MSW)
COVID cases in Beijing	−0.004 (0.005)	−0.001 (0.000)	−0.004 (0.005)	−0.001 (0.000)
COVID cases in China	0.083	0.013	0.082	0.013
COVID cases in China	(0.018)	(0.002)	(0.018)	(0.002)
Constant	11.433 (1.199)	4.101 (0.106)	11.491 (1.151)	4.103 (0.100)
Weekday FE	Yes	Yes	Yes	Yes
Community FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	6,421	6,420	6,421	6,420
r^2	0.402	0.613	0.402	0.613

Notes: This table shows the robustness check of the effects of the COVID-19 lockdown on the weight of MSW. Standard errors are clustered at the community level and are reported in parentheses.

4.3 Restriction of offline activities

To confirm that the decrease in MSW is the reduction of MSW generation and not the result of not being discarded, we further distinguish the effect of measures taken by the lockdown policy. In China, various measures were implemented, including restricting offline activities (e.g., dining, takeout, express delivery), closing workplaces and schools, and restricting public transportation. Although we could not distinguish the effect of each measure taken in January, the prevention measures to control a new round of the COVID-19 epidemic in Beijing offer an opportunity to test the effect of offline activity restriction.

After 56 consecutive days of zero new cases in Beijing, a new round of localized epidemics broke out at the Xinfadi market in Fengtai District, Beijing on June 12. The number of confirmed cases was 45 on that day, and several consecutive new cases were declared. The Fengtai District in Beijing rapidly took measures to control the epidemic on June 13. As for our sample community in Changping District, activities such as eating out and picking up express delivery were not restricted. However, mobility and public gathering activities were restricted, and schools closed again.

Utilizing this new round of control measures on June 13 as a placebo for the restriction of offline activities, we conduct the event study analysis with equation (2). Figure 6 reports the event study analysis of the placebo lockdown on June 13. We find insignificant decreases in both total MSW and average MSW per package after the new lockdown policy. The main difference between the June 13 lockdown and the first lockdown is that it did not strictly control offline activities, such as shopping, eating and express delivery. The insignificant coefficient in the placebo test indicates that offline activity restriction is the main driving force that reduces MSW. This finding implies that the lockdown changes consumer behavior and thus reduces the generation of MSW.

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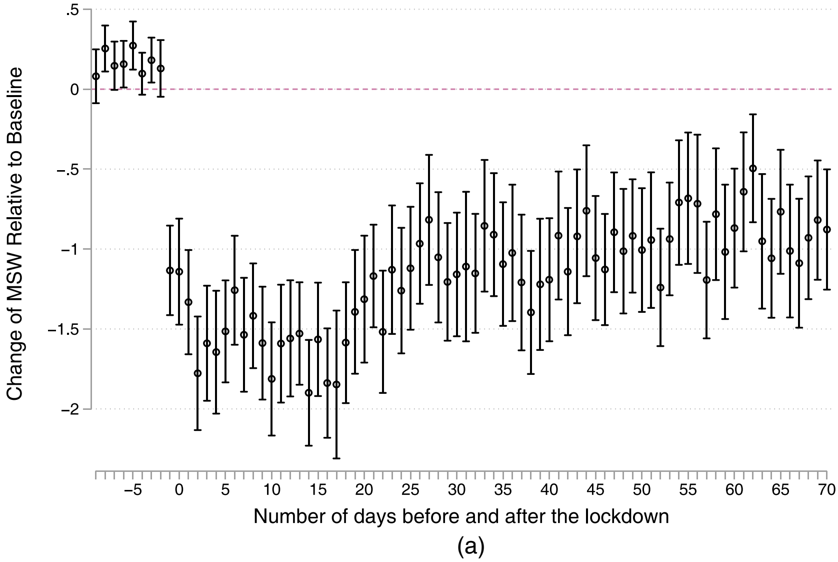

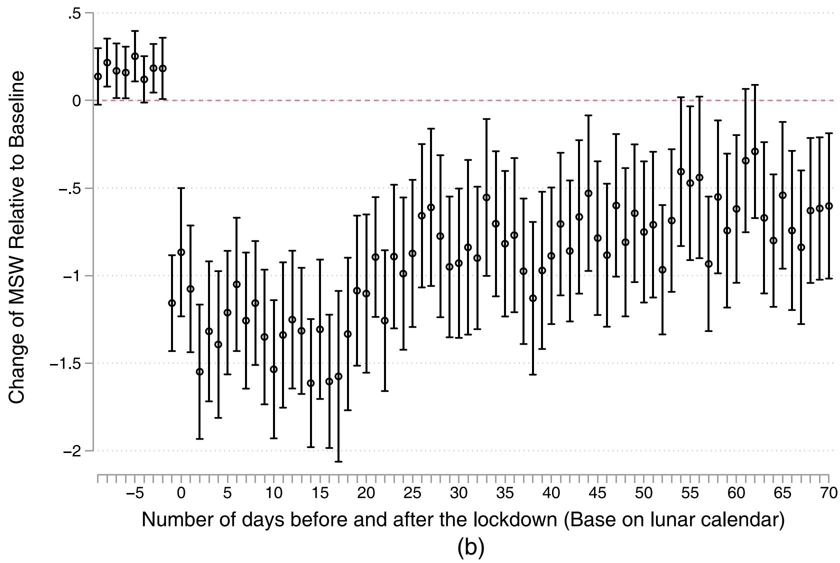

Figure 4. Long-term event study analysis: total MSW weight.
Notes: This figure reports the effects of the COVID-19 lockdown on the total weight of MSW and 95 per cent confidence intervals for the period from 9 days before to 70 days after the lockdown. The long-term window ends on April 2, 2020. Panel (a) reports the effect measured by the solar month model and panel (b) reports the results of the lunar month model. All models also include weather controls, community dummy, weekday dummy, and year dummy. The reference group is 10 days prior to the window. Standard errors are clustered at the community level

A multi-country survey has documented an increase in MSW in some countries other than China because of increased consumption of packaged food, fresh food, and food delivery during the lockdown (Leal Filho *et al.*, 2021), which is the opposite of our

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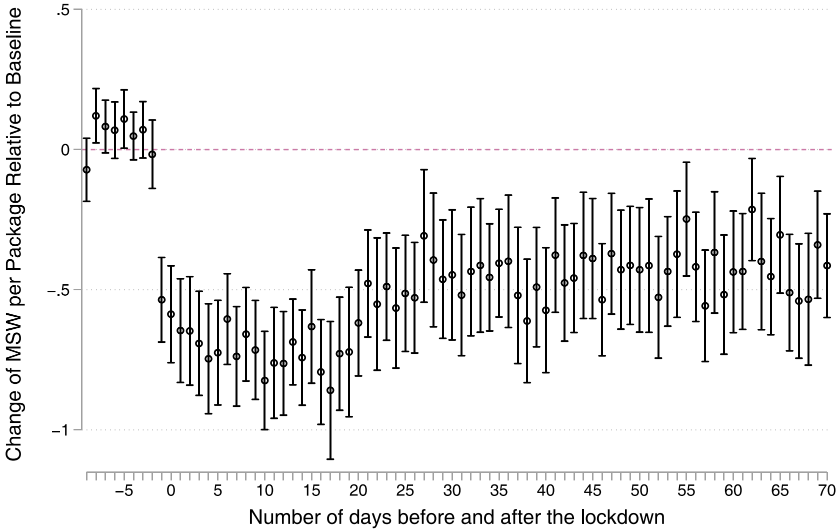
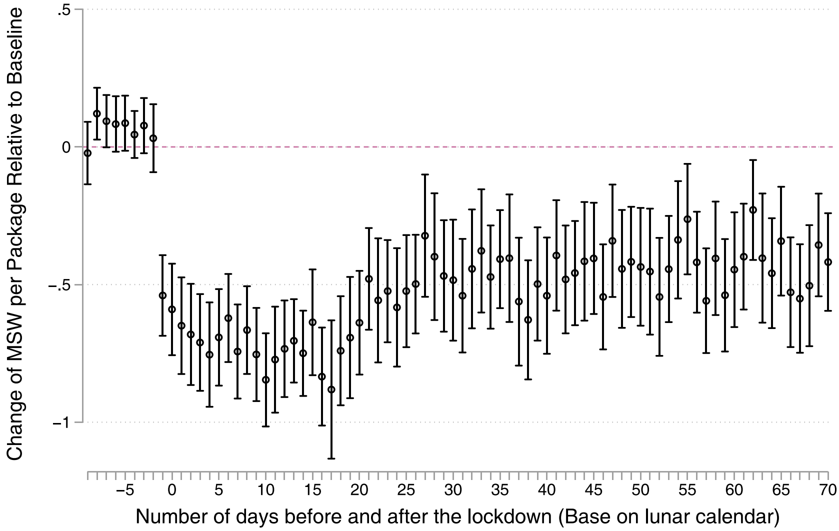


(a)



(b)

Figure 5. Long-term event study analysis: average MSW weight per package.
Notes: This figure reports the effects of the COVID-19 lockdown on the average weight of MSW per package and 95 per cent confidence intervals for the period from 9 days before to 70 days after the lockdown. The long-term window ends on April 2. Panel (a) reports the effect measured by the solar month model and panel (b) reports the results of the lunar month model. All models also include weather controls, community dummy, weekday dummy, and year dummy. The reference group is 10 days prior to the window. Standard errors are clustered at the community level.

result. However, our empirical results of the second round of lockdown point out that MSW does not decrease if offline consumption activities are not restricted. Unlike most countries, China's lockdown limits almost all consumption, especially food takeout and

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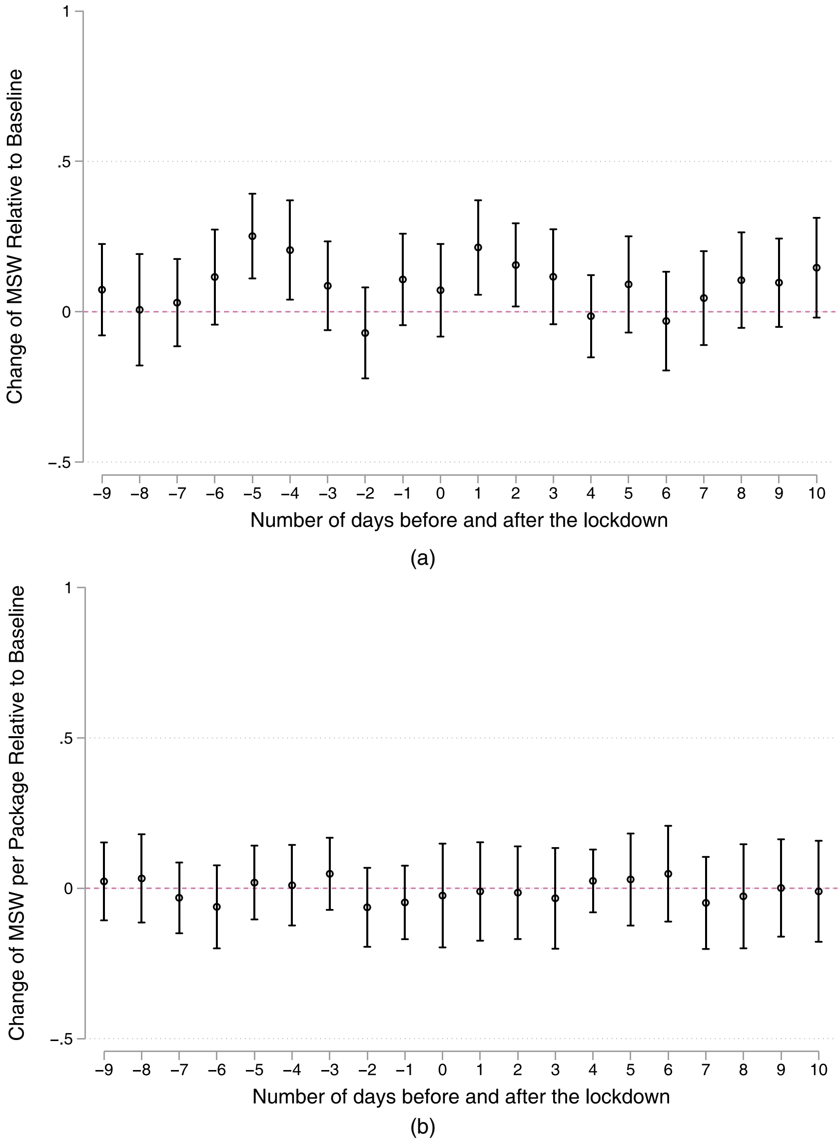

Figure 6. Placebo event study analysis.
Notes: This figure reports the effects of the placebo epidemic response on the weight of MSW and 95 per cent confidence intervals for the period from 9 days before to 10 days after the COVID-19 cases broke out without lockdown policy in Changping. Panel (a) reports the change in total MSW weight and panel (b) reports the change in average MSW weight per package. All models also include weather controls, community dummy, weekday dummy, and year dummy. The reference group is 10 days prior to the event window. Standard errors are clustered at the community level.

express delivery. Our findings are in line with the descriptive analysis of Fan *et al.* (2021), which finds a decrease in household waste in Shanghai and an increase in both Brno and Singapore. We provide evidence that the restriction of consumption decreases the amount of MSW at the source.

4.5 Fear of going out

A possible explanation for the decrease in MSW is that people are fearful of going out due to newly confirmed cases. We collect the geographical location and date of the local COVID cases to conduct an event-study analysis, which examines the effect of locally confirmed cases on MSW discarding behavior.

$$MSW_{cd} = \alpha + \Sigma_{j=-9}^{10}(\beta_{1j}\text{COVID}_c \times \text{day}_j) + \beta_2\text{After}_{cd} + \beta X_d + \pi_d + \mu_c + \varepsilon_{cd}, \quad (4)$$

where MSW_{cd} is the weight of MSW for community c on day d, which takes logarithmic form. COVID_c is a dummy variable that takes the value of 1 if the community is within a certain range of the new case. We follow Liu and Tang (2021) and select the 3 km, 5 km, and 10 km communities near the newly confirmed cases as the treatment group because they have a high exposure risk of infection. The window of interest is 10 days before and after the date of the case report in 2020 and we omit the −10 day, which means that the reference group is 10 days prior to the occurrence of the new case. All the local cases in the Changping District are confirmed after the implementation of the lockdown policy.

Figure A3 in the online appendix reports the effect of confirmed cases. The insignificant change of the coefficients suggests that the newly confirmed local cases have no effect on the discard of MSW. We use various definitions of the high exposure communities and the results are robust. The average MSW per package shows a similar pattern (see figure A3b). This finding shows that the adjustment of discarding behavior because households avoid going out for fear of infection is not the main reason for the reduction of MSW.

4.4 Suspension of work and school

Finally, we simply address the effect of the suspension of work and school that moved people's daily activities from their workplaces and schools to their homes. The concern is that the shift in people's place of daily activity may also shift where they generate and throw away the garbage, which may also affect the changes in MSW after lockdown.

However, we find certain facts that make the effect of shifts in places of daily activities less problematic for our analysis. First, the winter holiday of primary and secondary school students began on January 18 in Beijing, which means that the impact of school suspension on their daily place of activity can be ignored. Second, if the suspension of work shifts the place where people generate and discard garbage, an upward bias of the MSW weight is anticipated after the lockdown. However, we find that the total MSW still significantly decreased after the lockdown. Moreover, the decrease in the average MSW indicates the reduction of MSW generation. Overall, even if we consider the effect of the shift in discarding place, the lockdown still significantly reduced MSW.

5. Further analysis: community characteristics

The preceding section established the causal relationship between lockdown and MSW generation. Next, we examine the heterogeneous effect of the MSW decrease. The lockdown policy reduced the generation of MSW because of stores closing and a reduction in household daily consumption.

At least three main factors affect the reduction effect of MSW, considering that daily consumption, such as express delivery and food takeaway, is the main source of MSW. First, purchasing power affects the reduction of MSW. In the counterfactual situation

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without a lockdown policy, households with strong purchasing power will consume more. After the implementation of the lockdown, consumption was difficult for all families, thus reducing the generation of MSW. Therefore, households with strong purchasing power reduced MSW more after the lockdown. Second, the commercial supply around the community affects the reduction of MSW. The lockdown policy restricted nearly all commercial activities so that communities with more complete commercial facilities had more supplies shut down. Those communities with more complete commercial facilities reduced MSW more after the lockdown. Third, households may initiate a reduction in consumption behavior to reduce exposure, even reducing food, water and other necessary consumption items.

To examine the above effect, we estimate the regression allowing the heterogeneous effects. Specifically, we interact the cross term with the community characteristics:

$$\begin{aligned} MSW_{cdy} = \alpha + \beta_3 \mathrm{treat}_y \times \mathrm{After}_{cd} \times \mathrm{Char}_c + \beta_1 \mathrm{treat} \times \mathrm{After}_{cd} + \beta_2 \mathrm{After}_{cd} \\ + \beta_4 \mathrm{treat}_y + \beta X_{dy} + \pi_d + \mu_c + \varepsilon_{cdy}, \end{aligned} \tag{5}$$

where Char_c denotes the community characteristics, and all the other variables are defined similarly to equation (1). We take the logarithm of the average weight of MSW per package as the independent variable. Considering that we cannot directly measure household-level characteristics, we use community characteristics to represent family characteristics. Table 5 reports the heterogeneity effect of the MSW generation.

First, we use the average house price and the construction year of the house to proxy the purchasing power of the household.[13] The premise of this method is that the average house price and construction time are positively correlated with the household's purchasing power, which somewhat makes sense. Columns (1) and (2) report the estimation of purchasing power effect. The cross terms of house price and construction year are −1.787 and −0.019, respectively, and are statistically significant. These results indicate that households with high purchasing power will reduce MSW more after the lockdown.

Second, we take the dummy variables of whether the community has property services and the property service fees as proxy variables of the commercial supply.[14] This choice is reasonable because communities with sophisticated property services tend to have better commercial facilities, thereby anticipating many shops around. Columns (3) and (4) report the result of the cross terms of property service. The coefficients of property service dummy and property service are −0.388 and −0.415, respectively. The significantly negative coefficients suggest that the shutdown of shops around the community contributes to the reduction of MSW after the lockdown day.

Third, we estimate the effect of households actively reducing consumption to reduce disease exposure risk. We interact the cross term with the number of households in the community. Those who live with more neighbors face a higher exposure risk than those with fewer ones. Thus, they are more likely to reduce the opportunities for consumption and discarding. Taking the initiative to reduce consumption can reduce the generation of MSW, thus reducing the average weight of MSW per package. Taking the initiative to reduce the frequency of discarding will lead to the accumulation of garbage and increase the average weight of MSW per package. Column (5) reports the results of the cross term

[13] There is a correlation between the construction years and housing prices, because the earlier the construction of housing facilities, the lower the housing price.

[14] Property fee is a service fee per unit area, which is only related to community commercial services. Property services are fixed monthly, and do not change with the weight of waste disposal.

Table 5. Further analysis: municipal solid waste responses and community characteristics

	(1)	(2)	(3)	(4)	(5)
	Purchasing power effect		Supply shutdown effect		Consumption reduction effect
Panel A: Response of log MSW per package to lockdown by community characteristics based on solar calendar					
Treat × after × House price	−1.787 (0.525)				
Treat × after × Cons Year		−0.019 (0.009)			
Treat × after × Property service			−0.388 (0.187)		
Treat × after × Property fee				−0.415 (0.169)	
Treat × after × Household					−0.399 (0.092)
Treat × after	17.110 (5.483)	−1.688 (0.171)	−1.284 (0.158)	−1.235 (0.255)	1.038 (0.576)
Controls	Yes	Yes	Yes	Yes	Yes
Weekday FE	Yes	Yes	Yes	Yes	Yes
Community FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
N	5,214	5,242	6,420	3,945	5,325
r^2	0.652	0.649	0.639	0.636	0.661
Panel B: Response of log MSW per package to lockdown by community characteristics based on lunar calendar					
Treat × after × House price	−1.788 (0.525)				
Treat × after × Cons Year		−0.019 (0.009)			
Treat × after × Property service			−0.387 (0.187)		
Treat × after × Property fee				−0.415 (0.169)	
Treat × after × Household					−0.399 (0.092)
Treat × after	17.219 (5.483)	−1.586 (0.168)	−1.177 (0.163)	−1.156 (0.242)	1.132 (0.596)
Controls	Yes	Yes	Yes	Yes	Yes
Weekday FE	Yes	Yes	Yes	Yes	Yes
Community FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
N	5,214	5,242	6,420	3,945	5,325
r^2	0.652	0.650	0.639	0.636	0.661

Notes: This table shows the effects of the COVID-19 lockdown on the average weight per package of MSW and the heterogeneity effects with different community characteristics. Standard errors are clustered at the community level and are reported in parentheses.

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of household number, and the coefficient is −0.399, which is significant at the level of 1 per cent. This finding implies that households reduce their consumption and therefore reduce the generation of MSW.

6. Discussion

We have examined the effect of lockdown on MSW reduction and verified the underlying mechanism and various heterogeneity effects. Based on the previous findings, we discuss some important implications for the policy of MSW. First, our findings highlight the importance of MSW, which has not received considerable attention compared with the strong concerns over air and water pollution. MSW not only has a direct adverse health impact (Tomita *et al.*, 2020) but also leads to air (Muller *et al.*, 2011) and water pollution (Yu *et al.*, 2020). Therefore, our study compensates for the cost and benefit assessment of the lockdown policy by emphasizing the decrease in MSW.

Second, while the lockdown policy significantly decreased the generation of MSW, the high economic cost caused by the lockdown makes it hard to be considered as a long-term policy. Although MSW had not returned to the pre-epidemic level within half a year after lockdown, the gradually increasing trend suggests that taking a shutdown as a MSW management policy is unsustainable. A series of measures are being taken to reduce the adverse impact of MSW. From the perspective of end treatment, a series of environmental science research evaluated the environmental impact of MSW landfills and incineration (Assamoi and Lawryshyn, 2012) and offered many engineering solutions. From the perspective of source governance, the 3Rs principles – reduce, reuse and recycle – all help cut down on the amount of waste. Environmental economics has slowly shifted its attention to waste management. Valente and Bueno (2019) find that the Unit Pricing System leads to a 37.5 per cent reduction of household generation in Italy. Ek and Miliute-Plepiene (2018) identify the positive spillover of household waste activities; they find that the Swedish food collection policy has promoted a 5–10 per cent reduction of packaging waste. Akbulut-Yuksel and Boulatoff (2021) find that the green nudge policy increased households' recycling by 15 per cent and decreased the generation of MSW by 27 per cent. Compared with the above policies, we believe that the method of reducing MSW from the source is not limited to consumption restrictions, but also includes the price policy of internalizing pollution costs and green boost. Although we find that the reduction of MSW caused by the lockdown policy is among the largest (56.8 per cent), our findings provide an estimation of emission reduction potential for the source governance policy.

Third, we thus highlight the importance of source management in MSW governance. The COVID-19 lockdown offers us a natural experiment to test the effects of the change in consumption patterns on MSW. To control the outbreak of the COVID-19 pandemic, the lockdown policy closed nearly all the shops, banning regular daily consumption activities. Current evidence shows that the effect of the COVID-19 lockdown on MSW amount is ambiguous (Fan *et al.*, 2021; Leal Filho *et al.*, 2021). Our findings suggest that the reduction of MSW in China during the lockdown was mainly driven by consumption restrictions that change people's consumption patterns and reduce the MSW generation. We thus highlight the importance of source management in MSW governance. Reducing the production activities of MSW, such as the use of disposable goods, large use of express delivery, and over-packaging, can help reduce the cost of MSW classification, the cost of landfill and

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incineration treatment, and the negative externality on both the environment and public health.

Finally, the practical implication of our study is to call on the public to pay full attention to the external cost of MSW they ignored before, while considering the private cost of consumption. We call on the public to reduce unnecessary consumption to reduce the negative welfare impact of MSW.

7. Conclusion

This study provides the first empirical evidence of the effect of the COVID-19 lockdown on MSW. With a unique database of daily records of MSW discarding in Beijing, we identify the causal effect of lockdown and MSW and investigate the underlying mechanism. We find that the COVID-19-induced lockdown significantly decreased MSW. The event study results verified the robustness of our results. We further examine various explanations for the reduction of MSW. Our finding provides suggestive evidence that lockdown not only leads to the reduction of MSW discarding but, more importantly, it reduces the generation of MSW by changing people's consumption patterns. We also document heterogeneous impacts for different community characteristics. Our empirical work contributes to the emerging economic literature that examined the impact of COVID-19 and adds to a small set of studies on MSW. Our findings also have practical implications for calling on MSW reduction at the source and supporting the 3Rs principle.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1355770X22000353

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Conflict of interest. We, the authors of this paper, declare that: (1) we have no conflict of interest that could have appeared to influence the work reported in this paper, and (2) we have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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