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A cross-jurisdictional comparison on residential waste collection rates during earlier waves of COVID-19

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ABSTRACT

There is currently a lack of studies on residential waste collection during COVID-19 in North America. SARIMA models were developed to predict residential waste collection rates (RWCR) across four North American jurisdictions before and during the pandemic. Unlike waste disposal rates, RWCR is relatively less sensitive to the changes in COVID-19 regulatory policies and administrative measures, making RWCR more appropriate for cross-jurisdictional comparisons. It is hypothesized that the use of RWCR in forecasting models will help us to better understand the residential waste generation behaviors in North America. Both SARIMA models performed satisfactorily in predicting Regina's RWCR. The SARIMA D_{CV} model's performance is noticeably better during COVID-19, with a 15.7% lower RMSE than that of the benchmark model (SARIMA B_{CV}). The skewness of overprediction ratios was noticeably different between jurisdictions, and modeling errors were generally lower in less populated cities. Conflicting behavioral changes might have altered the residential waste generation characteristics and recycling behaviors differently across the jurisdictions. Overall, SARIMA D_{CV} performed better in the Canadian jurisdiction than in U.S. jurisdictions, likely due to the model's bias on a less variable input dataset. The use of RWCR in forecasting models helps us to better understand the residential waste generation behaviors in North America and better prepare us for a future global pandemic.

1. Introduction

An outbreak of a novel coronavirus (SARS-CoV-2) with rapid transmission has attracted global attention since December 2019, and COVID-19 was declared a pandemic by the World Health Organization in March 2020. Many countries have restricted the movement of their citizens and have locked down populated areas to contain the spread of the virus (Cheng et al., 2022; Moosazadeh et al., 2022). COVID-19 has led to a dramatic loss of human life across the globe, posing unprecedented challenges to every aspect of our lives (Qadeer et al., 2022; Wang et al., 2021; Wang & Huang, 2021), including the sustainable management of municipal solid waste (MSW) (Mahyari et al., 2022). For instance, the elevated amount of personal protective equipment such as masks, disposable gloves, and face shields has brought major challenges to the operation of waste management systems, which have been well discussed in literatures (Hantoko et al., 2021; Wang et al., 2021; Pourebrahimi, 2022).

1.1. Effects of COVID-19 on solid MSW generation and collection

Proper waste management promotes good public hygiene, helping us to better recover from a global pandemic and to build more resilient cities. Blasi et al. (2022) reviewed 9206 papers on smart cities and sustainable development goals (SDG) and found that "waste management" were commonly discussed in SDG studies. Given its significance, many studies have reported the effects of COVID-19 on various waste management issues (Mahmud et al., 2022; Requena-Sanchez et al., 2022; Sarmento et al., 2022). The literature suggest that the generation and collection of MSW emerged differently under different administrative measures throughout the stages of pandemic. For instance, the reported generation rates of plastic waste, food waste, and biomedical waste are not entirely consistent. An increase in plastic waste was attributed to the increased consumption of plastic packaged foods (Oliveira et al., 2021) and single-use plastics (Qadeer et al., 2022) during the COVID-19 pandemic. On the other hand, the economic recession and interrupted production considerably reduced plastic usage

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List of acronyms

AVG_a	average or arithmetic mean of the dataset
IQR	Interquartile Range
MSW	Municipal Solid Waste
RMSE	Root Mean Square Error
RWCR	Residential Waste Collection Rate
SARIMA	Seasonal Autoregressive Moving Average
SD_a	Standard Deviation

in the automotive and aviation (Klemeš et al., 2020), transportation (Fan et al., 2021), and construction (Fan et al., 2021) industries. Similar inconsistencies have been observed in various food waste studies. For instance, conscious buying helped reduce food waste during COVID-19 (Rodgers et al., 2021; Rai et al., 2023), whereas panic buying due to the fear of running out of supplies was responsible for increased food waste (Zhao & You, 2021). Inconsistencies in the literature are also observed in biomedical waste generation behaviors. An enhanced sense of hygiene (Sangkham, 2020; Katal et al., 2022) and increased number of COVID-19 infected cases (Valizadeh et al., 2021; Thakur, 2022) contributed to an increase in biomedical waste generation in some places. Conversely, avoiding hospitals and healthcare facilities as a vector for COVID-19 resulted in an abrupt decrease in biomedical waste generation, especially during the earlier waves of COVID-19 infections (Richter et al., 2021a; Singh et al., 2022a). The suspension of recycling programs (Zambrano-Monserrate et al., 2020; Olatayo et al., 2021) and restricted manual sorting (Hantoko et al., 2021; Penteado & Castro, 2021) during COVID-19 could have artificially inflated MSW disposal rates, as less recyclable materials are being diverted from landfills. Inconsistencies in COVID-19 waste data trends make factor identification challenging, affecting the development of versatile forecasting models for effective waste management planning.

Unlike MSW generation rates, the reported MSW collection rates in literatures are, however, much more consistent. In this study, MSW collection rate is defined as the amount of waste materials collected from residential areas by a municipal government via a publicly funded program or by a waste service provider on behalf of the local municipality. In most municipalities, MSW collection rates are considerably less than MSW generation rates, as other waste streams (institutional, commercial, industrial, and construction and demolition wastes) are mostly excluded from the residential stream. According to a U.S. study, the amount of waste collected from residential areas increased by as much as 14% during the COVID-19 pandemic across three U.S. states, Florida, New York, and California (Pinto et al., 2022). In a Canadian capital city, a significant increase in residential waste was observed during the early waves of the pandemic (Richter et al., 2021b). The reported increase in the residential waste collection during COVID-19 corresponds well with the regulators' administrative measures restricting business operations and commercial activities (Zambrano-Monserrate et al., 2020; Sarmento et al., 2022). The widely adopted work-from-home arrangement, social distancing, restricted traveling, and self-isolation may have also resulted in more residential waste. For instance, Hantoko et al. (2021) studied COVID-19 waste management issues at a global level and argued that waste collection frequency should be increased to address the surges in residential waste.

1.2. Quantitative waste forecasting during COVID-19

The literature review suggests that COVID-19 waste forecasting studies are mostly focused on MSW disposal rates and not on MSW collection rates. Vu et al. (2021a) built a recurrent neural network (RNN) model using separated waste fractions to predict COVID-19 waste disposal rates in the City of Regina, Canada. Vu et al. (2021b) further improved the performance of the RNN waste disposal model by incorporating exogenous variables such as lagged inputs and achieved a mean absolute percentage error below 10%. More recently, Jassim et al. (2023) proposed a BiLSTM network model and predicted the waste disposal rates in Bahrain using historical landfill records. Modeling with MSW disposal rates could help us to understand the factors affecting the waste generation behaviors in a broader sense, as multiple waste streams are considered (Vu et al., 2021a). However, the MSW disposal rate is more sensitive to changes in waste management regulations and administrative measures. In North America and many other places, MSW is commonly quantified by weight. A small decrease in construction activities due to COVID-19 restrictions could have heavily skewed the MSW disposal rates given the density of construction and demolition waste, making data analysis of MSW disposal models more challenging.

COVID-19 administrative measures vary temporally and spatially and largely depend on the socioeconomic status of a municipality (Ebner & Iacovidou, 2021; Mofijur et al., 2021). Conventional modeling of MSW disposal rate makes cross-jurisdictional comparisons challenging, given their sensitivities to administrative measures. Instead, the current study focuses on the modeling of the residential waste collection rate (RWCR). It is hypothesized that the modeling of RWCR could better capture the effects of COVID-19 on residential waste generation characteristics. The use of RWCR in waste modeling is believed to be more advantageous during a pandemic as it allows rapid comparisons between jurisdictions with varying degrees of waste management regulations and administrative measures.

1.3. SARIMA models in waste forecasting

Seasonal variations of MSW generation characteristics and recycling behaviors have been well documented and discussed (Denafas et al., 2014; Edjabou et al., 2018), and various numerical models have been proposed (Adusei et al., 2022a, 2022b; Sarmento et al., 2022). Many waste researchers have applied Seasonal Autoregressive Integrated Moving Average (SARIMA) models in quantitative forecasting due to the model's ability to capture seasonal and non-stationary behaviors of time series. Navarro-Esbrí et al. (2002) examined datasets with strong seasonal patterns and concluded that SARIMA models could achieve 20.0% lower relative errors than non-linear dynamic models regardless of the forecast horizon. Xu et al. (2013) reported that SARIMA-based models perform adequately when seasonal dynamics exist in time series. Their models' absolute percentage errors were near or below 3.0% when applied in the case study in Xiamen, China (Xu et al., 2013). Sarmento et al. (2022) applied SARIMA models to predict COVID-19 residential waste collection rates in Lisbon, Italy and obtained satisfactory model performance. Sarmento et al. (2022)'s findings also suggested that COVID-19 administrative measures might play a role in restoring the seasonality in MSW collection trends. Since RWCR datasets are expected to exhibit seasonal patterns (Vu et al., 2020; Richter et al., 2021b), SARIMA models are adopted in the current study.

1.4. Objectives, novelties, and implications

The key study objectives are to [i] predict residential waste collection rate (RWCR) during COVID-19 period in a Canadian capital city using SARIMA models, and [ii] compare the SARIMA models' performance across the jurisdictions in North America. Unlike most waste modeling studies with a focus on MSW disposal rates (Adusei et al., 2022b; Vu et al., 2022a; Jassim et al., 2023), this study focused solely on the RWCR derived from municipal programs. Conventional modeling of MSW disposal rates during the pandemic may be less applicable for cross-jurisdictional comparisons, given their sensitivity to COVID-19 regulatory and administrative measures and diverse climatic conditions. It is hypothesized that the use of RWCR in forecasting models will help us to better understand the residential waste generation behaviors in North America during a global pandemic.

This study fills the knowledge gap on the effects of COVID-19 and its associated administrative measures on residential waste generation characteristics and recycling behaviors. Residential waste generation characteristics in North America were destabilized during earlier waves of COVID-19 (Ikiz et al., 2021; Richter et al., 2021b), yet studies on waste forecasting models seldom take waste collection rates into consideration. Variations in residential waste generation during COVID-19 could strain the efficient operation of a waste collection service (Kulkarni & Anantharama, 2020). As such, a more accurate RWCR forecast model could be useful in developing efficient and data-driven residential waste management policies for a future pandemic.

2. Methodology

Fig. 1 outlines the principal steps of the approach used in this study. An overview is provided here, and details are discussed in Sections 2.1–2.3. A total of four North American cities are selected, and waste data are separately collected, verified, and processed. Two SARIMA models were first developed to model the RWCR in Regina, the capital city of Saskatchewan, Canada. The selected SARIMA model is then applied in three U.S. cities with different socioeconomic conditions to predict RWCR. Comparisons of model performance on accuracy and consistency were made across the Canadian and U.S. jurisdictions. The proposed analytical approach using RWCR contributes to our understanding of residential waste generation and recycling behaviors during a global pandemic.

2.1. Study areas

Regina, the capital city of Saskatchewan, Canada, was selected to develop the SARIMA models. The solid waste management system in Regina during and before the pandemic has been well documented (Richter et al., 2021a; Vu et al., 2021b; Mahmud et al., 2022) and is used to develop a benchmark model in the current study. Three additional U.S. cities (Austin, Seattle, and Buffalo) with different socioeconomic and climatic conditions were carefully selected for cross-jurisdictional comparisons. Given the health and safety concerns, accurate waste data are particularly scarce during the earlier waves of COVID-19 (Wang et al. 2021b). All selected U.S. jurisdictions have publicly available and verifiable waste datasets (City of Austin, 2021; City of Buffalo, 2022b; City of Seattle, 2022b). The model performances in all four jurisdictions were compared to test the limits of the SARIMA models in predicting RWCR.

All four of the selected North American cities have their respective publicly-funded curbside waste collection programs during the study period. Regina has curbside pickup services for waste and recyclables for a majority of residential units city-wide (City of Regina, 2022). Austin Resource Recovery is responsible for collecting curbside residential waste, including garbage, organics, and recyclables in Austin City of Austin, (2020). The Sanitation Department and Recycling Department of the City of Buffalo deal with the collection of municipal refuse and recyclables from residents (City of Buffalo, 2022a). In Seattle, residential waste collection is provided by two service providers, and the total tonnage of garbage, organics, and recyclables is reported (City of Seattle, 2022a).

2.2. Data collection and processing

Minor inconsistencies in waste statistics are not uncommon in Canada and were well reported (Wang et al., 2016; Chowdhury et al., 2017). The daily RWCR in Regina from 2013 to 2020 were collected and meticulously verified using historical waste records. The daily rates were then aggregated into monthly data, making Regina's dataset comparable to the three U.S. datasets. The monthly Canadian dataset was used to develop two benchmark models (SARIMA B_{CV} and D_{CV}, as discussed in Section 2.3) to examine the effect of COVID restrictions and regulations in Regina. The best benchmark model in Regina was then applied to three other U.S. jurisdictions. The monthly RWCR from 2014 to 2020 in Austin, Seattle, and Buffalo were separately collected from

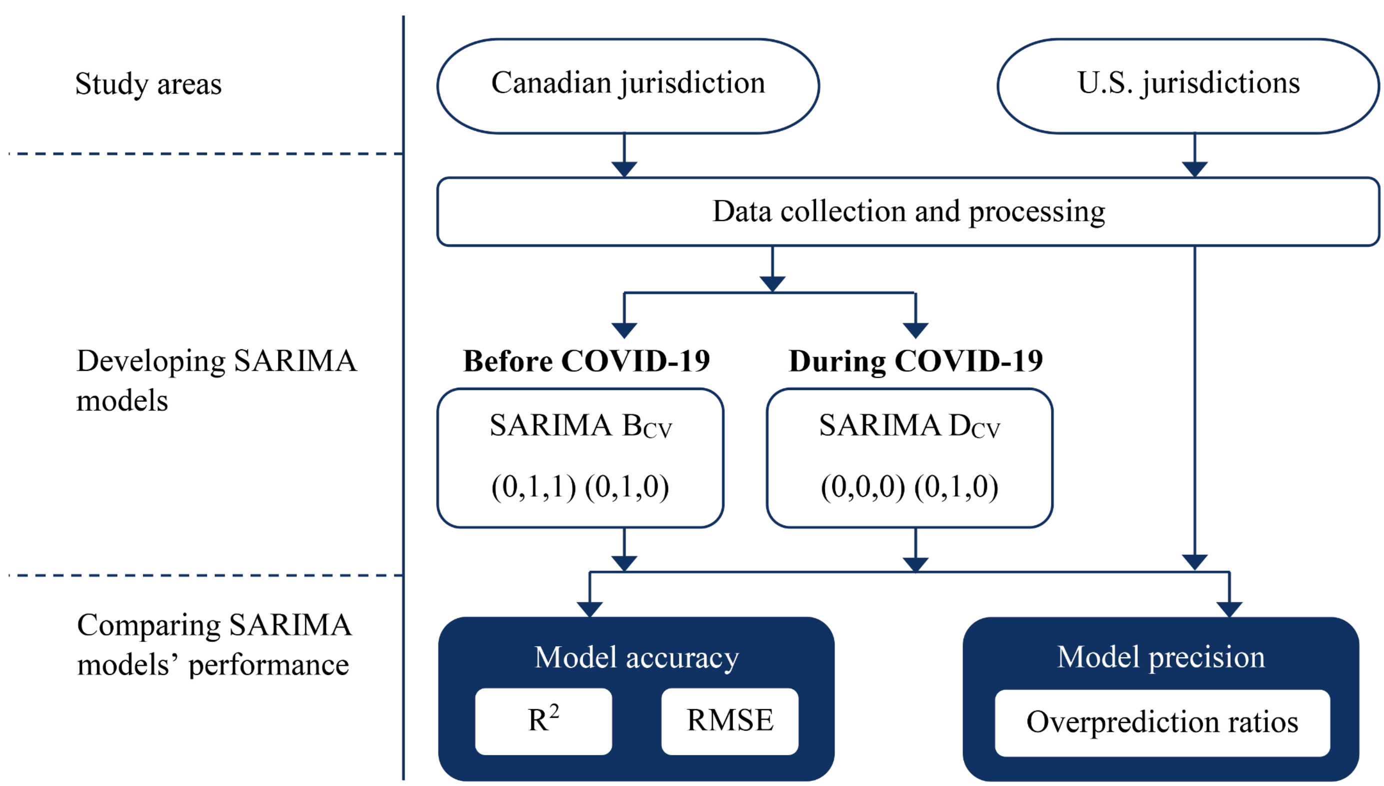

Fig. 1. Study approach (Note: "B_{CV}" represents before COVID-19 and "D_{CV}" represents during COVID-19).

their respective government portals (City of Austin, 2021; City of Seattle, 2022b; City of Buffalo, 2022b).

Each dataset contains 80 months of residential waste collection tonnages. A data partition of 70:15:15 was adopted for all four datasets (Hoque & Rahman, 2020; Ayeleru et al., 2021). About 70% of the data was allocated for model training. The remaining 30%of the data was split equally between the validation and testing phases. In other words, the model performance will be based on the differences between the estimated RWCR and the actual RWCR in 2020. These city-wide data were obtained to compare the performance of the SARIMA models across jurisdictions.

2.3. SARIMA model building and prediction

2.3.1. Model background

SARIMA models are based on autoregression and moving average models that include a backshift for trend and seasonality while forecasting a time-series, and they are commonly adopted in waste studies (Xu et al., 2013; Sarmento et al., 2022; Wang et al., 2022). To predict a time-series $\{Y_t\}$, SARIMA (p,d,q)(P,D,Q) model can be described by Eq. (1):

$$\phi_p(B)\phi_P\left(B^S\right)(1-B)^d\left(1-B^S\right)^D Y_t = \theta_q(B)\theta_Q\left(B^S\right)\varepsilon_t \quad (1)$$

where: p, d, q = the order of autoregression, regular differencing order, and the order of moving average, respectively (non-seasonal).

P, D, Q = the order of autoregression, seasonal differencing order, and the order of moving average, respectively (seasonal).

ε_t = residuals

S = periodicity of season

B = backshift operator

$\phi_p(B)$ = non seasonal autoregression component = $1-\phi_1 B-\phi_2 B^2-\ldots-\phi_p B^p$

$\phi_P(B^S)$ = seasonal autoregression component = $1-\phi_1 B^S-\phi_2 B^{2S}-\ldots-\phi_P B^{PS}$

$\theta_q(B)$ = non seasonal moving average component = $1-\theta_1 B-\theta_2 B^2-\ldots-\theta_q B^q$

$\theta_Q(B^S)$ = seasonal moving average component = $1-\theta_1 B^S-\theta_2 B^{2S}-\ldots-\theta_Q B^{QS}$

2.3.2. Model development

In this study, two SARIMA models - SARIMA (0,1,1)(0,1,0) and SARIMA (0,0,0)(0,1,0) were developed using the Canadian dataset to predict RWCR in 2019 and 2020, respectively. These two models are hereinafter referred to as "SARIMA B_{CV}" and "SARIMA D_{CV}", respectively. The use of the two distinct models will help us better understand residential waste generation characteristics before and during the implementation of COVID-19 regulatory and administrative measures. The effects of COVID-19 on MSW generation and recycling behaviors have been observed across the globe, and the development of a pre-COVID-19 benchmark model (the "SARIMA B_{CV}") helps us to verify the accuracy and precision of the SARIMA D_{CV} model. All SARIMA models were developed using R (version 4.1.3), an open-source programming environment used for statistical computing. In this study, the model best fit is determined by the auto.arima() function within the fpp2 package (Hyndman & Athanasopoulos, 2018), available on the Comprehensive R Archive Network repository. The auto.arima() function has been customized to comb through possible models and select the best-fit model. The customization was done by setting arguments according to Hyndman and Athanasopoulos (2018).

2.3.3. Model performance assessment

2.3.3.1. Overprediction ratio. In this study, an overprediction ratio was used to compare both the accuracy and precision of SARIMA models. An overprediction ratio is defined by the predicted RWCR over the actual RWCR in the testing period, as shown in Eq. (2). The overprediction ratio is a dimensionless parameter, and it has been used in waste studies (Can, 2020; Vu et al., 2021a) when comparing the accuracy of the prediction of different forecasting models. A ratio of unity suggests perfect prediction. The precision of models can be obtained from comparisons of the ratios.

$$\text{Overprediction ratio} = \frac{\text{Predicted RWCR (tonne/month)}}{\text{Actual RWCR (tonne/month)}} \quad (2)$$

2.3.3.2. Performance indicators. To compare the forecasting accuracy of SARIMA (p,d,q)(P,D,Q) models, both scale-dependent and scale-independent performance indicators were selected. As shown in Eq. (3), Root Mean Square Error (RMSE) is scale dependent, and a lower RMSE denotes a more accurate model. A coefficient of determination (R^2) of unity indicates better agreement between the predicted and the actual values, as shown in Eq. (4). Both RMSE and R^2 have been widely adopted in waste studies to assess the model performance (Ayeleru et al., 2021; Karimi et al., 2021; Xu et al., 2021). The following equations were used to calculate these performance indicators.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Y_o^i - Y_f^i\right)^2} \quad (3)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Y_o^i - Y_f^i\right)^2}{\sum_{i=1}^{n}\left(Y_o^i - \overline{Y}\right)^2} \quad (4)$$

where:

n = size of the sample

Y_0^i = observed residential waste collection rate

Y_f^i = forecasted residential waste collection rate

$\overline{Y}$ = mean observed residential waste collection rate

In addition, the sensitivity of SARIMA models' performance to statistical and climatic variables is discussed separately to identify their impact on the models' performance. The sensitivity was investigated using Pearson correlation analysis. A Pearson correlation coefficient closer to unity indicates a perfect linear correlation, whereas a near zero value implies that no linear correlation exists within the selected pair of variables. The statistical variables (i.e., SD_a and AVG_a) used in this study reveal the characteristics of the input dataset for SARIMA models. As shown in Eqs. (5) and (6), the standard deviation (SD_a) and mean (AVG_a) indicate the spread and average of the actual RWCR dataset, respectively.

$$SD_a = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_o^i - \overline{Y}\right)^2}{n-1}} \quad (5)$$

$$AVG_a = \frac{\sum_{i=1}^{n} Y_o^i}{n} \quad (6)$$

Seasonality plays a key role in the accuracy of the SARIMA models. Previous studies documented the effect of climatological variables on the performance of waste prediction models (Vu et al., 2019, 2021b). Hence, the climatological data of each jurisdiction were collected to investigate their effect on SARIMA models' performance. These climatic variables include temperature, precipitation, and humidity. The monthly average temperature and precipitation data of the Regina, Austin, Seattle, and Buffalo were collected from the Government of Canada (2022), National Weather Service (2022a), National Weather Service (2022b), and National Weather Service (2022c), respectively. The daily humidity data were collected from Weather Underground (2022a), Weather Underground (2022b), Weather Underground (2022c), and Weather Underground (2022d), respectively. The monthly and daily climatological data were scaled to create a yearly dataset.

3. Results and discussions

3.1. SARIMA model performance, seasonality, and COVID-19 measures

The SARIMA models' performance indicators are shown in Fig. 2. SARIMA models appear to capture the residential waste collection in Regina well. Both models performed satisfactorily, with R^2 values of 0.78 and 0.89 for SARIMA B_{CV} and SARIMA D_{CV}, respectively (Fig. 2). Rosecký et al. (2021) reported that at a regional level, waste prediction models could be useful when R^2 ranged from 0.32 to 0.86. A similar R^2 range was reported by Sarmento et al. (2022). It appears that the model performance improved during the COVID-19 period, and the SARIMA D_{CV} model is able to capture the RWCR more accurately. Compared to the benchmark model in 2019 (SARIMA B_{CV}), SARIMA D_{CV}'s R^2 value was 14.1% higher, and RMSE was 15.7% lower (Fig. 2). Sarmento et al. (2022) reported similar relationships between seasonality and MSW collection trends.

Since the amount of waste generated in households varies seasonally (Adelodun et al., 2021; Yang et al., 2022), RWCRs are also expected to fluctuate throughout the year. In Fig. 3, the boxplots show the ratios of predicted and actual RWCR in Regina over the four seasons. A horizontal bar within the box represents the median, and an asterisk indicates the mean. The boxes' lower and upper extremities correspond to the first and third quartiles, respectively. The minimum and maximum values are denoted by the whiskers outside the box.

Fig. 3a shows the overprediction ratios of SARIMA B_{CV}, while Fig. 3b depicts the same for SARIMA D_{CV}. Both Regina models underestimated the RWCR, as the average overprediction ratios are slightly less than 1.0. In the case of SARIMA B_{CV} (Fig. 3a), the average overprediction ratios ranged from 0.948 to 0.972, whereas the medians were between 0.917 and 1.022. The Summer set appears normally distributed in Fig. 3a, with a mean of 0.972 and a median of 0.970. A consistent skewness of the SARIMA B_{CV} sets is not observed among the four seasons. The sets were obviously skewed in Spring and Fall in 2019 but in the opposite direction. On the other hand, the averages of the overprediction ratios of SARIMA D_{CV} in 2020 were more consistent, ranging between 0.917 and 0.978 (Fig. 3b). The skewness of the sets was also consistent among the seasons. All sets appear negatively skewed, with medians higher than the mean. It appears that the COVID-19 work-from-home measures improved the seasonality of the residential waste generation behaviors. Compared to the benchmark (SARIMA B_{CV}), less variations were generally observed in 2020 (Supplementary Fig. 1). The interquartile range (IQR) of the overprediction ratio varied significantly between SARIMA B_{CV} in 2019 and SARIMA D_{CV} in 2020. With the exception of Winter, less scattering is observed in 2020 (Fig. 3b) than in 2019 (Fig. 3a), indicating higher precision of the SARIMA D_{CV}. The IQR of SARIMA B_{CV}'s overprediction ratio was 0.036 in Winter 2019 (Fig. 3a), about 2-times less than that of SARIMA D_{CV}. One possible explanation is an unusually harsh Winter in 2019. A significant difference in average ambient temperature was observed between Winter 2019 (−16 °C) and Winter 2020 (−10 °C) in Regina (Government of Canada, 2022). As a result of the colder average temperature in Winter 2019, residents might have avoided outdoor activities and stayed indoors for a longer period (Vu et al., 2021b; Adusei et al., 2022a). Consistency in waste generators' behaviors appears to improve both the accuracy and precision of the SARIMA B_{CV}. The seasonal variations in waste generation behaviors are also reported in Adusei et al. (2022b). In general, RWCR predictions during COVID-19 were more consistent than those before COVID-19, probably due to the city-wide COVID-19 restrictions and measures. As such, the SARIMA D_{CV} model is selected for cross-jurisdictional comparisons.

3.2. RWCR during COVID-19 pandemic across Canadian and U.S. jurisdictions

The boxplots in Fig. 4 compare the performance of SARIMA D_{CV} models across different jurisdictions in 2020. The mean overprediction ratio of SARIMA D_{CV} was between 0.862 and 0.984, and the median ranged from 0.864 to 1.018 across Canadian and U.S. jurisdictions. It appears that the SARIMA D_{CV} consistently under-predicted RWCR during COVID-19. This finding is consistent with a general increase in residential waste in 2020 due to the work-from-home policies.

Distinctive differences were observed in the mean overprediction ratios across the four jurisdictions; however, no obvious pattern was observed. With the exception of Buffalo, SARIMA D_{CV} generally under-predicted the RWCR during Spring and Summer more than it did during Winter. This could be due to abrupt changes in household waste composition and quantity during the early waves of COVID-19 in the Spring and Summer of 2020. The change in residential waste composition and quantity could be attributed to COVID-19-induced behavioral changes among waste generators, including panic buying (Lahath et al., 2021; Tang et al. 2021), stockpiling (Babbitt et al., 2021; Tang et al. 2021), online shopping (Filho et al., 2021; Mouratidis & Papagiannakis 2021), and increased sense of hygiene (Patrício Silva et al., 2020;

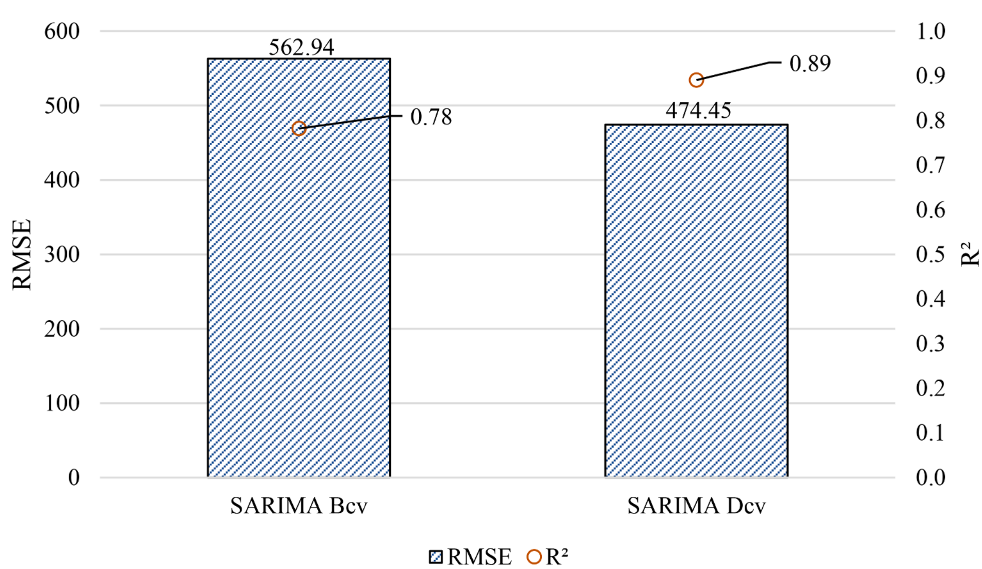

Fig. 2. Performance of the Seasonal Autoregressive Integrated Moving Average models using Regina dataset.

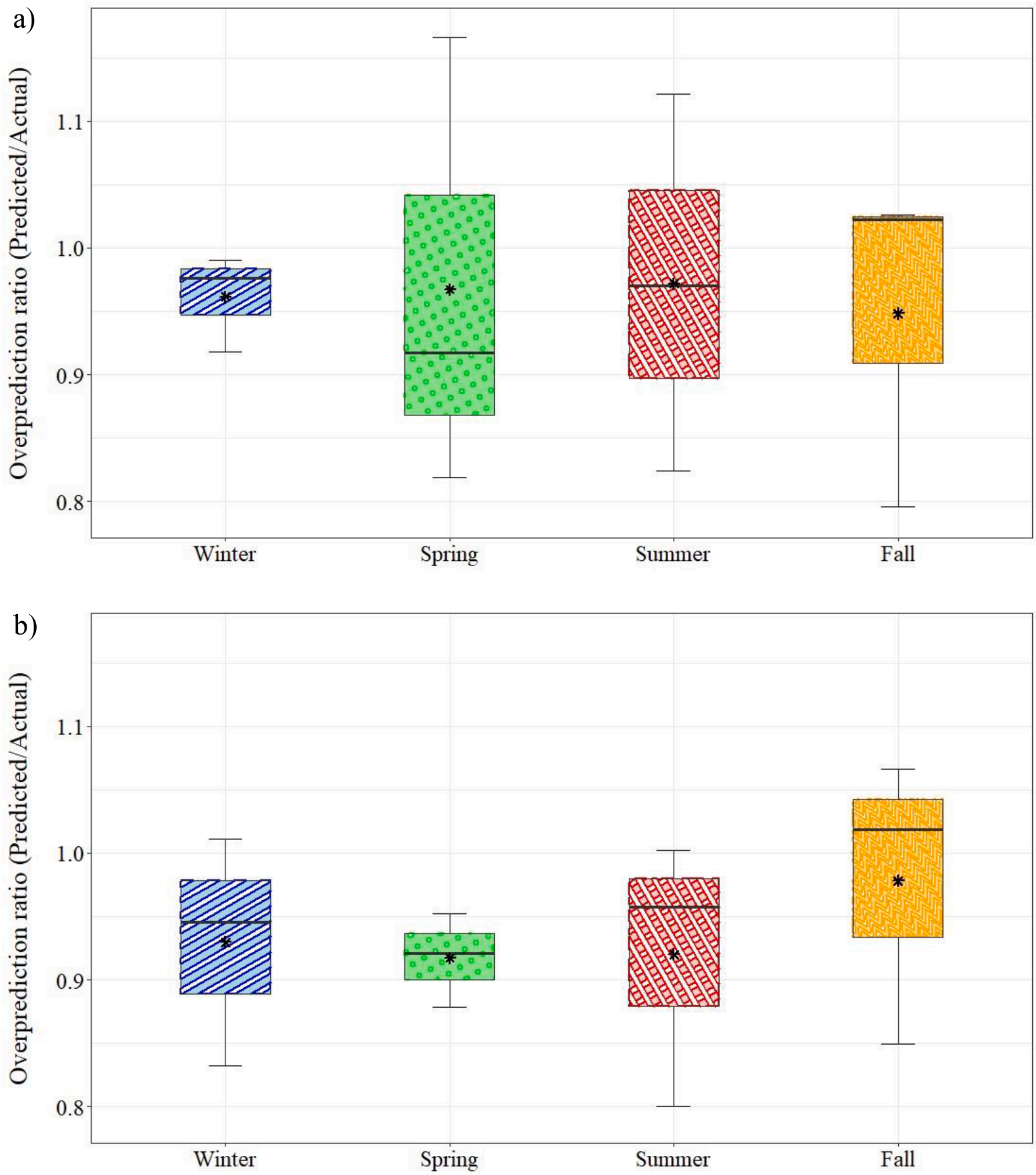

Fig. 3. Effects of seasonality on model accuracy and precision using (a) SARIMA B_{CV} and (b) SARIMA D_{CV}.

Shakibaei et al. 2021). It appears that as opposed to the short-term positive repercussions of COVID-19 administrative measures on the environment by reducing carbon emission (Wang & Wang, 2020) and water pollution (Qadeer et al., 2022), MSW management was adversely affected by the destabilization of the residential waste collection rates.

The skewness of overprediction ratios was noticeably different between Canadian and U.S. jurisdictions. Unlike its U.S. counterparts, the Regina set is negatively skewed among the seasons. During the later waves of COVID-19 in 2020, the performance of SARIMA D_{CV} varied across the jurisdictions, likely due to their differences in the evolution of residential waste generation characteristics and recycling behaviors. Even after the initial waves of COVID-19, continued reliance on online food delivery services and extensive use of PPE might have increased household waste towards the end of 2020 (Mallick et al., 2021; Haque & Fan, 2022). Similar negative impact of waste generators' behavioral changes on household waste has also been reported in other parts of the world (Argentiero et al., 2022; Singh et al., 2022b). On the contrary, adaptation to precautionary health measures (Burlea-Schiopoiu et al., 2021; Blazy et al., 2021) might have helped reduce residential waste during the later waves of COVID-19. These conflicting behavioral changes might have altered the RWCR differently across the jurisdictions and affected the predictability of SARIMA D_{CV}.

The variability of the overprediction ratio might also be sensitive to the duration of COVID-19 lockdowns. All of these North American cities implemented lockdowns and other similar regulatory measures in the Spring of 2020. The IQR of the overprediction ratio in Austin was 3 to 4 times higher than in Seattle, Buffalo, and Regina (green boxes, Fig. 4). Since the COVID-19 lockdown in the City of Austin was withdrawn shortly (Moreland et al., 2020), more outdoor activities during late spring might have impacted the residential waste composition and quantity and increased the variability of SARIMA D_{CV} predictions in Austin.

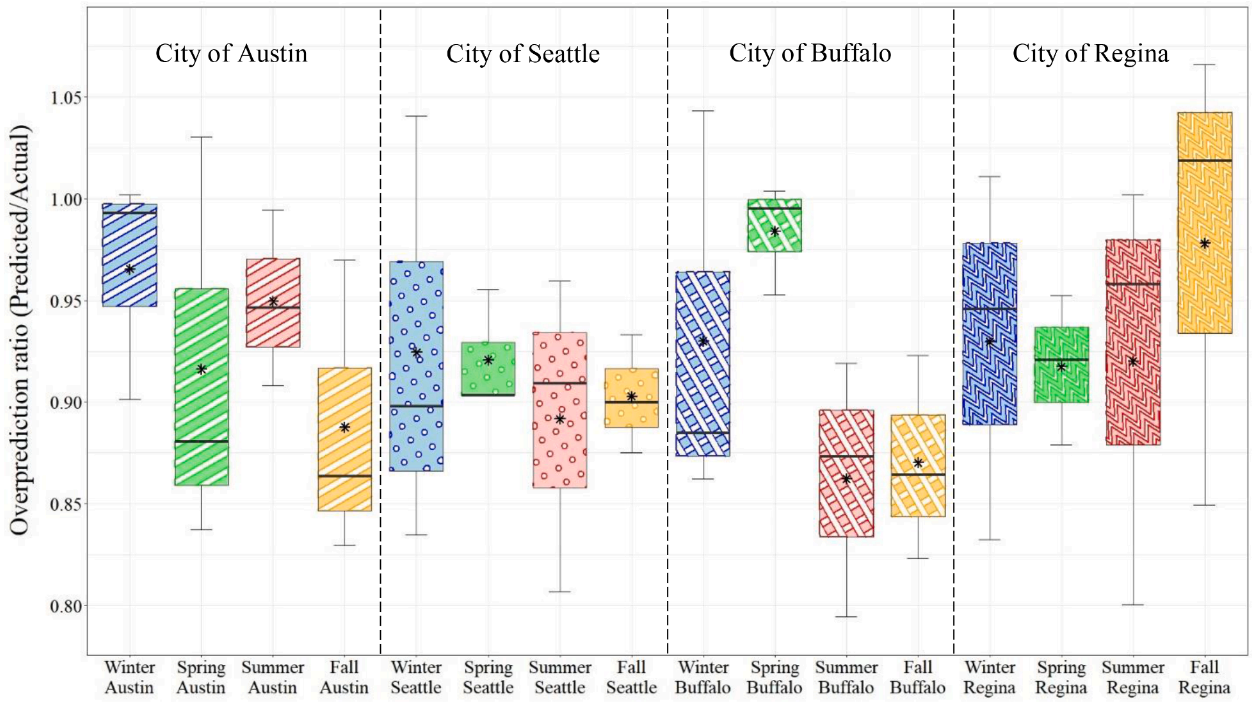

Fig. 4. Accuracy and precision of SARIMA D_{CV} in four North American cities.

3.3. Overall performance of Sarima models in predicting RWCR during COVID-19 across North American jurisdictions

A summary of the performance of SARIMA D_{CV} across different Canadian and American jurisdictions is shown in Fig. 5. Different RMSEs are obtained due to the differences in residential waste tonnages across the jurisdictions. Modeling errors are considerably lower in less populated cities (i.e., Regina and Buffalo). A relatively wide range of R^2 from 0.51 to 0.89 is observed (Fig. 5). Among the selected jurisdictions, SARIMA D_{CV} performed best in the Canadian jurisdiction. The Regina model's R^2 is about 24–76% higher than that of the American jurisdictions. Some studies (Kannangara et al., 2018; Hu et al., 2021) reported an association between the size of the dataset and the performance of prediction models. However, a consistent size of datasets is used in this study. The statistical and climatic factors affecting SARIMA D_{CV} model performance will be further discussed in the next section.

3.3. Statistical and climatic factors of model performance

The results of the Pearson correlation analysis for the statistical and climatological variables are shown in Fig. 6. The blue-colored cells indicate a positive relationship, and the red ones represent a negative relationship. The corresponding statistical significance is denoted by an asterisk above the correlation coefficient. The asterisks are in an incremental order, indicating $p < 0.05$, $p < 0.01$, and $p < 0.001$.

The average yearly humidity and total precipitation do not seem to significantly affect the performance of SARIMA D_{CV} (row 5 & 7 of column 2 & 3 in Fig. 6). However, the average yearly temperature was found to have a statistically significant negative correlation with the

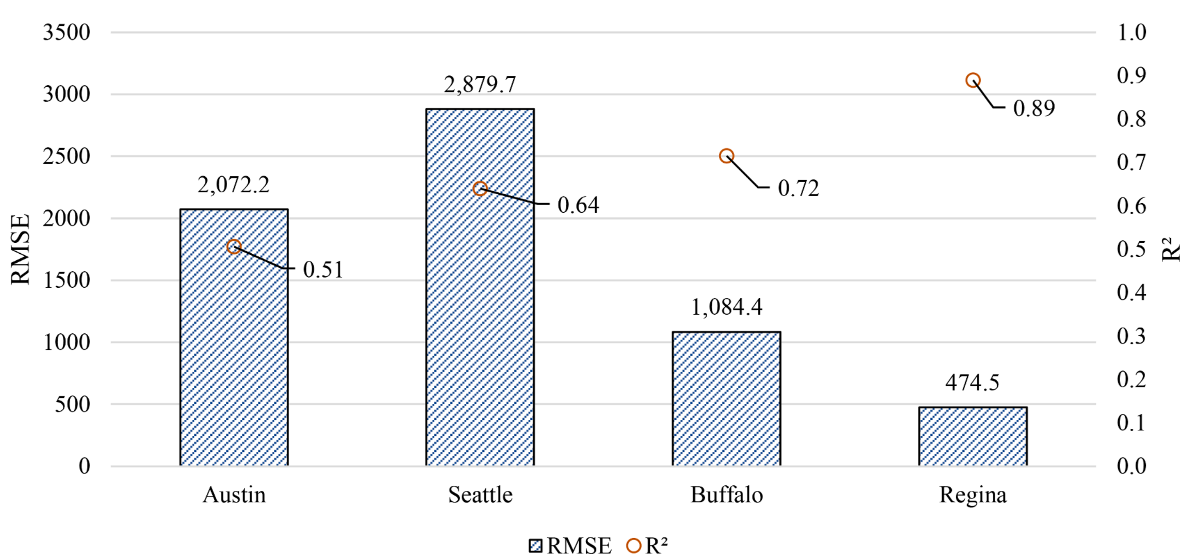

Fig. 5. Model performance of SARIMA D_{CV} across North American cities.

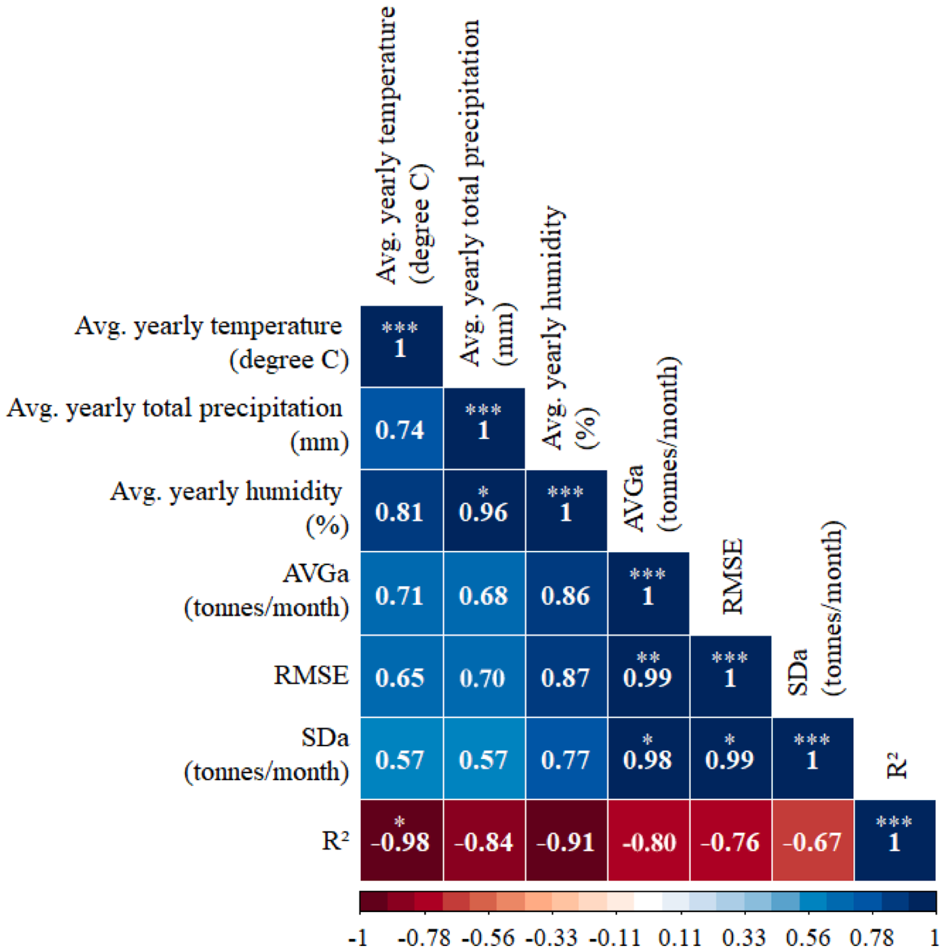

Fig. 6. Correlation between statistical variables, climatic variables, and performance indicators of SARIMA D_{CV}.

performance indicator, R^2 of the SARIMA D_{CV} (coefficient = −0.98, p-value<0.05). Residents usually avoid outdoor activities on colder days (Lin & Ling, 2021; Paukaeva et al., 2021), which might make household waste generation behaviors more uniform, resulting in a more consistent residential waste collection dataset. Ambient temperature is identified as a significant factor on residential waste collection rates. Similar results are observed in SARIMA B_{CV} (Supplementary Fig. 2).

The characteristics of the dataset appear to be important to the performance of the model. The standard deviation (SD_a) is positively correlated with RMSE (coefficient = +0.99, p-value<0.05). Similarly, the AVG_a is positively correlated with the RMSE (coefficient = +0.99, p-value<0.01). These findings suggest that SARIMA D_{CV}'s bias is sensitive toward the distribution of waste data. Similar findings are observed in the SARIMA B_{CV} (Supplementary Fig. 2). As such, the models might be more suitable for jurisdictions with a less variable residential waste collection dataset. Vu et al. (2022b) examined the waste disposal model in Regina and reported that variations in the datasets lead to significant variations in model performance.

4. Conclusions

Most waste studies focused on "generation rates" estimated from recycling data and landfill disposal records, which are sensitive to COVID-19 regulatory and administrative measures. The literature review suggests that there is a lack of COVID-19 waste studies on residential waste collection in North America. RWCR is relatively less susceptible to the changes in local waste management policies and is more appropriate for cross-jurisdictional comparisons. As such, this study predicted RWCR using SARIMA models across different North American jurisdictions before and during the pandemic.

Both SARIMA models performed satisfactorily in predicting Regina's RWCR with R^2 > 0.70. The SARIMA D_{CV} model's performance is noticeably better during COVID-19, with a 15.7% lower RMSE than that of the benchmark model (SARIMA B_{CV}). Higher consistencies of the SARIMA D_{CV}'s average overprediction ratios between 0.917 and 0.978 were observed, likely due to the elevated RWCR during the lock-downs and the work-from-home orders. Different skewness and variability in the overprediction ratios between SARIMA B_{CV} and SARIMA D_{CV} were observed. The IQRs of the overprediction ratio of SARIMA D_{CV}'s were nearly 2 to 5 times lower than SARIMA B_{CV}. SARIMA D_{CV} generally underestimated RWCR during COVID-19, perhaps due to an overall increase in RWCR in Spring 2020. With the exception of the City of Buffalo, the mean overprediction ratios were lower (i.e., between 0.892 and 0.950) during the early waves of COVID-19 in Spring and Summer 2020 than that in Winter 2020. The early COVID-19 administrative measures caused an abrupt increase in RWCR, affecting the model accuracy. The skewness of overprediction ratios was noticeably different between jurisdictions. Unlike its U.S. counterparts, the Regina set is negatively skewed among the seasons. Modeling errors are considerably lower in less populated cities. Conflicting behavioral changes might have altered the residential waste generation characteristics and recycling behaviors differently across the jurisdictions.

Overall, SARIMA D_{CV} performed better in the Canadian jurisdiction than in U.S. jurisdictions, with a 24%−76% higher R^2 and 56%−84% lower RMSE, likely due to the sensitivity of the model's bias on the variability of waste dataset. Hence, attention should be given while interpreting the results of SARIMA models for highly variable input sets. The use of RWCR in waste modeling studies are recommended. This study calls for more research on residential waste generation behaviours during a global pandemic, which has received very little attention.

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.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2023.104685.

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