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Promoting digital transformation in waste collection service and waste recycling in Moscow (Russia): Applying a circular economy paradigm to mitigate climate change impacts on the environment

Aleksandra Maiurova [a,1], Tonni Agustiono Kurniawan [b,*,1], Marina Kustikova [a], Elena Bykovskaia [a], Mohd Hafiz Dzarfan Othman [c], D. Singh [d], Hui Hwang Goh [e]

[a] Faculty of Energy and Ecotechnology, ITMO University, St Petersburg, 197101, Russia
[b] College of Environment and Ecology, Xiamen University, Xiamen, 361102, Fujian province, PR China
[c] Advanced Membrane Technology Research Centre (AMTEC), School of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia
[d] Faculty of Digital Transformation, ITMO University, St. Petersburg 197101, Russia
[e] School of Electrical Engineering, Guangxi University, Nanning, 530004, Guangxi, China

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ABSTRACT

Due to industrialization, recently Moscow (Russia) has been inundated with municipal solid waste (MSW), while the capital does not have an organized waste collection and waste recycling system. Digitalization enables smart cities such as Moscow to do more work with less resources. This article identifies and analyzes the existing waste management facilities in Moscow with respect to drawbacks and the ways forward to mitigate the bottlenecks. To improve its waste management, lessons drawn from Berlin's experiences in waste management are discussed to inspire a transformation in the city's waste sector in the framewok of resource recovery. In line with the 2030 UN Agenda, this work proposes a digitalization to accelerate a societal transition through waste recycling industry. Its global relevance is elaborated by presenting a perspective of digitalization in waste management practices. In this work, case-study was selected as the research method to provide a means to investigate a complex waste problem in Moscow and Berlin (Germany). It was evident from a cleaner production paradigm that digital technology can minimize the amount of unrecycled MSW, while conserving raw materials and reducing operational cost and GHG emissions. Digitalization builds cities' resilience by strengthening local waste management practices to respond to the Covid-19 global pandemic. In Moscow, the transition towards the digitalization of waste recycling through informal waste sectors has created 5,000 new jobs that reduces unemployment rate. This maximizes pick up time and enhances efficiency with a lower cost of operating trucks up to 75%. A convolutional neural network–based identification system that classifies identified materials yields almost perfect accuracy. A single robot arm can handle four varying fractions of construction and demolition waste with 99% of purity. Robotic deployment could reduce the volume of unrecycled waste by 20%. This could be replicated worldwide to resist the pressure of resource consumption and deliver socio-economic and environmental benefits.

1. Introduction

As the world's largest transcontinental country (Fig. S1), in recent years Russian Federation has undergone a transformation due to rapid economic growth and urbanization. The country's population swelling and industrialization have led to the generation of huge amounts of waste. Although the urbanization itself is not a problem, unplanned growth has led to the overburden of municipal solid waste (MSW) generation.

The MSW refers to household waste and other waste related to economic or public activities including restaurant and schools, while MSW management (MSWM) covers the process of collection, haulage, recovery, and disposal of waste conducted by local authorities (Timofeeva et al., 2021). The growth of MSW in Russian urban cities might have outpaced the rapid growth of their population recently. Dumping it

* Corresponding author.
E-mail address: tonni@xmu.edu.cn (T.A. Kurniawan).
[1] Both the first and the second authors equally contributed to this article and mutually share the first authorship.

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List of abbreviations

4IR	4th Industrial Revolution
AI	artificial intelligence
BSR	Berliner Stadtreinigung
C&D	construction and demolition
CE	circular economy
Covid-19	corona virus disease
EU	European Union
GDP	gross domestic product
GHG	greenhouse gas emissions
GREP	German Resource Efficiency Program
GRP	gross regional product
GSDS	German Sustainable Development Strategy
ICT	information communication and technology
IMF	International Monetary Fund
IoT	internet of things
ISWM	integrated solid waste management
IT	information technology
LFG	landfill gas
ML	machine learning
MOBA	mobile automation
MSW	municipal solid waste
MSWM	municipal solid waste management
Mt	metric ton
PAYT	pay-as-you-throw
RFID	radio-frequency identification
SDG	sustainable development goals
UN	United Nations
UNCED	United Nations Conference on Environment and Development
USD	US Dollar
WMS	waste management system

directly to the landfills without proper recycling can damage the environment.

With an area of 17.13 million km^2 and a total population of 146 million in 2021 (O'Neill, 2021), the country is rich with natural resources. However, recently it has encountered uncontrolled MSW generation due to changes in consumptive style. A slight increase in income can change consumption patterns, which shift to more waste-intensive goods and increase the quantity of MSW. This poses challenges for Russia to handle and treat the MSW post-consumption (Kurniawan et al., 2022a).

In 2020, the total of annual MSW generation in Russia reached up to four billion Mt (Fig. 1) (Ministry of Natural Resources of Russia, 2020). Out of it, 1.75% (70 million) represents the MSW, while the rest is non-organic waste (Fig. 2). Although the MSW is a tiny fraction of the total waste in Russia, efficient and effective management of its MSW is essential due to its direct effects on the environment.

As the largest economy in the Russian Federation in terms of gross regional product (GRP), Moscow alone contributes 20% to the country's GDP (Elagina, 2021). Its 12 million of inhabitants generated about 8.05 million Mt of MSW in 2020 with its per capita ranging from 1.13 to 1.37 kg/day (Zorpas et al., 2021). Unless properly tackled, this would lead to a backlog of the MSW in the urban environment sooner or later. In the long-term, this will derail the country's development towards environmental sustainability (Fig. 3). If infrastructure investment were falling short, cash-strapped municipalities in Russia with inadequate infrastructures would find themselves with daunting backlogs.

While the country continues to grapple with on-going Covid-19 pandemic, it also encounters enormous tasks of reducing CO_2 emissions. Urban cities in Russia have encountered challenges in protecting public health and the environment from climate hazards, while tackling local development issues such as abating their GHGs. Russia must not take her eye off the climate change, as over a half of the global GHGs has been emitted from the transcontinental region (Kurniawan et al., 2022b).

Climate change is an urgent and existential threat to future generations. This will alter the ways of producing goods, means of transportation, and ultimately, the way in which people live. The burdens and causes of climate change are unevenly distributed over the world, and future generations will suffer much more. Its impacts on human lives are difficult to comprehend.

As the world is at the beginning of such a transformation, which can

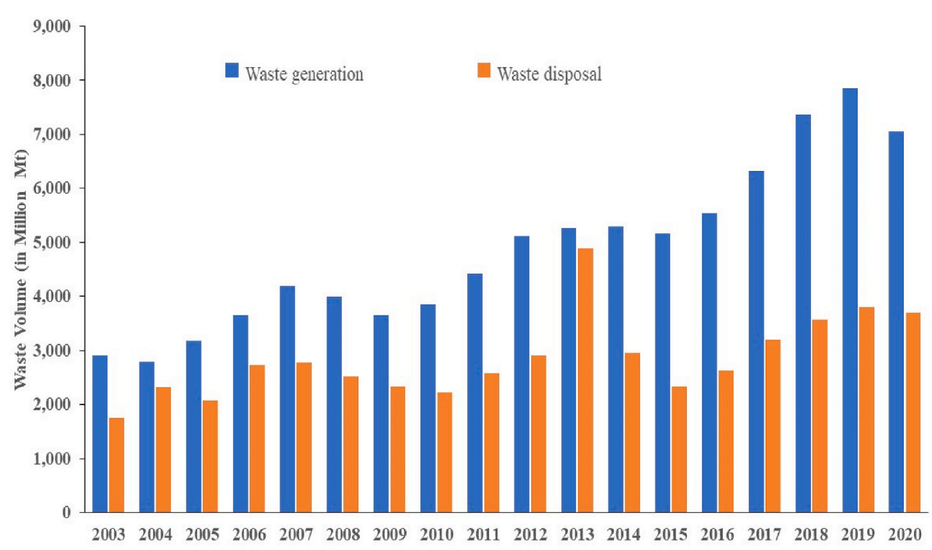

Fig. 1. MSW generation and disposal rate in Moscow (2003–2020).
(Source: Ministry of Natural Resources of Russia, 2020)

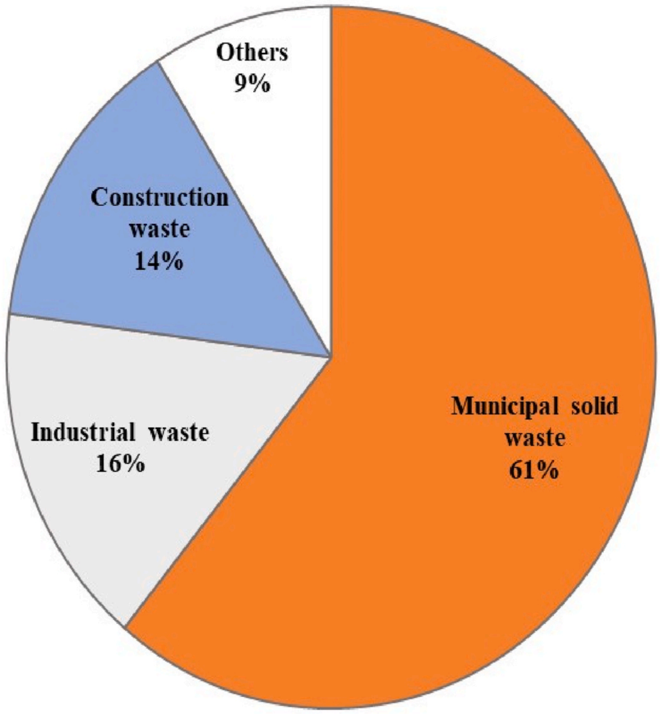

Fig. 2. Composition of waste generation in Russia in 2020.
(Source: Ministry of Natural Resources of Russia, 2020)

bring both benefits and new inequalities, current production and consumption patterns must be completely transformed if countries want to limit the rise of the Earth's atmospheric temperature to less than 1.5 °C. If the commitment is seriously enforced to attain net-zero emission, by 2070 the world shall no longer emit any GHG. This situation is 'sink or swim' for cities in their fight against climate change. Therefore, developing smart cities requires a new approach in the framework of digitalization (Ruohomaa and Ivanova, 2019).

While all countries have to build on the 2015 Paris Agreement to address this challenge together, Russia has intensified its transformation towards smart cities to sustain the country's growing urban population with respect to public health, socio-economic, and environment. Smart city is a framework of information and communication technology (ICT) that develops, deploys, and promotes sustainable best practices to address climate challenges through AI and/or ML (Loizia et al., 2021a). To facilitate net zero-emission, digital intelligence provides smart cities with a set of know-how to improve their quality practically by doing more work with less resources. This intelligent network connects objects and machines citywide by transmitting data using wireless technology and cloud (Loizia et al., 2021b).

For this purpose, Russian cities need to apply resource recovery paradigm to improve waste separation and recycling through digital solutions. Digital technologies are practical to implement, lessens the need of labor and equipment, and requires less maintenance and operation. When the recyclables are separated from non-recyclables at sources, unused non-biodegradable waste could be a source of raw materials that reduces the extraction of natural materials. On the other hand, poor waste treatment could waste potential recyclable materials and increase the consumption of scare and critical raw materials, bringing the negative impacts of waste on the environment (Abylkhani et al., 2021).

The implementation of resource recovery in recent years has enabled waste problems to be tackled using various ways to bring cumulative impacts on a global scale. The novelty of the resource recovery paradigm is underpinned by the fact that incorporating digital technologies into waste recycling is essential to address ecological and health implications in the Industry 4.0 era (Kurniawan et al., 2021a).

As traditional recycling practice reaches the limit of its capability, digital technology can minimize the amount of unrecycled MSW, while conserving raw materials and reducing operational cost and GHG emissions. These aspects of cleaner production are relevant to all industry, regardless of type or size. Although digital solutions are not a panacea for dealing with the urban problems, they can promote progress in cities if being coupled with appropriate policies. Therefore, integrating suitable technologies and/or relevant policies are required to harness socio-economic benefits after transforming the waste sector from being a source of GHG emissions to becoming its major net reducer; from being a part of environmental problems to becoming a part of sustainability solutions (Zorpas et al., 2018).

Preliminary studies on MSW management in Moscow undertaken by Mingaleva et al. (2020) as well as Wang and Li (2021) focused on the aspect of smart cities in Russia. In spite of their novelty, the studies did

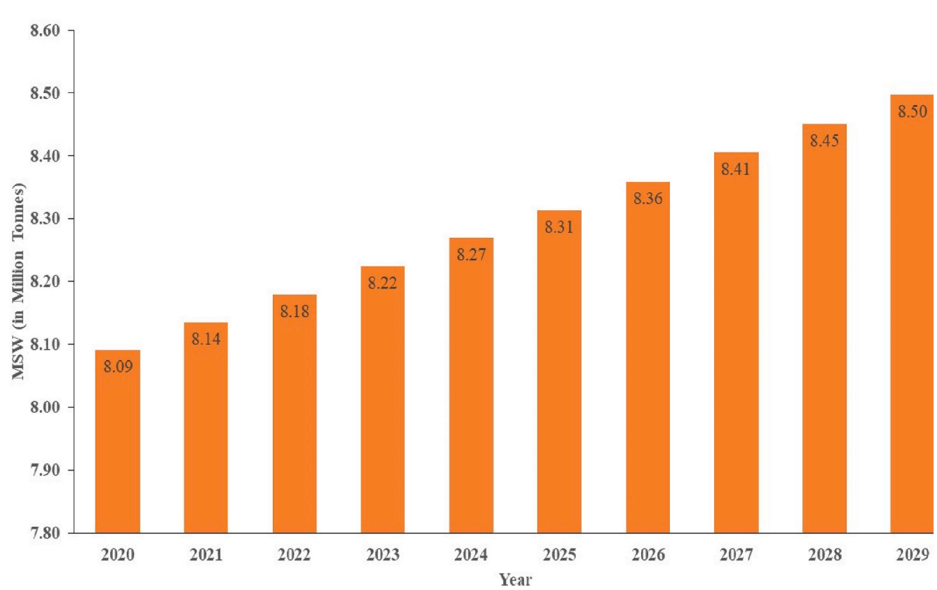

Fig. 3. Long-term projection of waste generation in Russia (2020–2029).
(Source: Ministry of Natural Resources of Russia, 2020)

not directly integrate digitalization as a part of sustainability solutions in Russia. Intelligent methods for re-use and recycling of waste materials were not established in their study, although both AI and ML might facilitate the transition required in the waste sector. There is a growing need to apply the digital solutions for promoting traceability of waste flows (Fedotkina et al., 2019). Considering current urban and societal development, AI and ML need to be applied to address cities' demand to make the required transformation in the waste sector. However, to the best of our knowledge, so far none in the body of literature has investigated the digitalization of waste management in Moscow (Russia) based on Berlin's mature experiences.

To align with the journal's special issue on 'smart technology for waste elimination', this article investigates current sustainability transition of MSW management in Moscow based on Berlin's proven experiences in the waste sector through integrated waste recycling and digital solutions. While Berlin has recovered up to 60% of its MSW using the approach, Moscow's waste recovery rate is almost zero. If this trend persists, the Russian capital has to double its MSW disposal capacity within the next decade to accommodate the growing volumes of its waste. Russia can improve its waste recycling industry by applying Berlin's successful experiences in reforming its MSWM.

To reflect its novelty, this article identifies and evaluates the existing waste management facilities in Moscow with respect to their drawbacks and the ways forward to mitigate their bottlenecks. To improve its waste management, lessons drawn from Berlin's experiences in waste separation and recycling are analyzed to inspire a transformation in the city's waste sector in the paradigm of resource recovery. In line with the 2030 UN Agenda, this work proposes a disruptive digitalization to accelerate a societal transition in the waste recycling industry. Global relevance of the work is also elaborated by presenting a perspective of digitalization in waste management practices.

It is anticipated that Berlin's successful experiences in MSW management would enable Moscow to transform its waste sector into an ISWM. This will accelerate a sustainability transition in waste industry through digitalization (Fig. 6). A sound MSWM in Moscow could promote the effectiveness of urban development with resource recovery approach to promote a societal transition in the long-run. As an important hub in the Russian Federation, Moscow can draw lessons from Berlin's experience as a smart city to improve the level of its MSW management (Gao, 2020).

Eventually, scientific contributions of this work will build public knowledge about the role of digital solutions for waste management and enhance their understanding on the impacts of digital transformation on society, economy, and the environment, raising awareness of relevant stakeholders. The results of this work will improve policymakers' understanding of how technological intervention in waste management can lead to Moscow's transition towards sustainable future through resilience, recovery, and net-zero emission amidst the Covid-19 global pandemic.

2. Methods

This case-study addresses how an integrated waste management with digitalization that controls MSW generation in Berlin could be emulated in Moscow in a comparative context (Ragin and Becker, 2020). Despite both Germany and Russia have a different level of capacity to govern, administrative capability, and innovation capacity, it is hypothesized that the case-study of MSW management in Berlin (Germany) could be transferable and applicable to Moscow (Russia) in terms of best waste management practices in smart cities using digitalization.

Case-study was selected in this work since it provided a means to investigate a complex waste problem by understanding its management in Moscow and Berlin. This method facilitated the authors to collect information that would not be obtained using other methodologies. The data obtained from this work were also of greater depth than those obtained using other designs.

2.1. Study areas

2.1.1. Moscow (Russia)

Geographically, Moscow is situated between 55°45′ North latitude and 37°36′ East longitude. The country's capital is located in the center of the East European Plain between the Oka and Volga rivers, at the junction of the Smolensk-Moscow Upland (in the west), the Moskovretsko-Oka Plain (in the east) and the Meshchera Lowland (in the southeast). With an area of 2,561 km^2 and a total population of about 13 million people, Moscow has a population density of 4,926 people per km^2 in 2019. In terms of administrative management, Moscow is divided into 12 regions ("*okrugs*"), 125 districts, and 21 settlements (Fig. S2).

As the center of the country's economic growth, the volume of the Moscow's economy in 2018 was RUB 15.7 trillion (US$ 0.21 trillion), ranking the 3rd among European cities. The gross domestic product (GRP) of Moscow grew to RUB 20 trillion in 2020 (US$ 0.27 trillion), while its GDP was RUB 1.5 million (US$ 20,000) per capita, approximately 2.5 times higher than that of national level on average (Analytical Center for the Government of the Russian Federation, 2020a; 202 b).

2.1.2. Berlin (Germany)

Geographically, Berlin is located in 52° 30′ North latitude and 13° 25′ East longitude (Fig. S3). As one of the most populated cities in the European Union (EU), Berlin is situated in the northeastern Germany on the River Spree. With an area of 892 km^2 and a population of 4 million, the population density of the German capital in 2020 was 4,463 inhabitants per km^2. The metropolitan consists of 12 districts such as Charlottenburg-Wilmersdorf, Friedrichshain-Kreuzberg, Marzahn-Hellersdorf, Mitte, Lichtenberg, Neukölln, Pankow, Spandau, Reinickendorf, Steglitz-Zehlendorf, Tempelhof-Schöneberg, and Treptow-Köpenick (Fig. S4).

Each district has advanced infrastructures for waste management from collection, transportation, and recycling to waste disposal. For this reason, Berlin was used as a model of smart city that has applied a resource recovery paradigm to optimize the consumption of scarce and rare materials and conserve resources. The capital is a miniature of Germany with a sustainable waste management to protect the environment and mitigate climate change by decoupling economic growth from resource use based on digitalization. As there are similarities between Berlin and Moscow in terms of urban construction and economic development, conceptually the former's successful experience in MSWM is significant to inspire the latter's urban development for using digitalization to improve its MSWM.

In addition, German know-how and experience in the waste sector have become a role model for other nations in managing their own MSW using digitalization. This makes the German's capital suitable and relevant as a case-study for Moscow. As the largest city in the country, Moscow was selected to represent Russia due to its relatively developed infrastructures and huge waste generation.

2.2. Data acquisition

To implement this study, the data were collected from primary and secondary sources for both the capitals. Initially, a literature survey was carried out to analyze written documents on German and Russian environmental policies such as "Digital Economy of the Russian Federation" and the Federal Law no. 89-fz/1998 as well as the "Waste Management Act of the German Federal Government (Kreislaufwirtschaftsgesetz)" and the EU Waste Framework Directive (2008/98/EC). The EU Directive aims at improving environmental protection and resource efficiency sustainably in waste management (Fedorov and Kuznetsova, 2020). The secondary data on their Statistics of MSW were supplementary.

Primary data were collected from semi-structured interviews with relevant stakeholders. This approach was effective to understand what took place by asking critical questions and evaluate events with them.

Respondents were also queried for their interaction with the digital apps in their cities, if they were aware with the apps, and the level of their satisfaction with them. We tested the actual apps existed in each capital and compared how users in different cities addressed the same questions. As the data used in this research were qualitative, they should be perceived as indicators only.

2.3. Data analysis

As one of the contributing factors to the 2030 UN SDGs, CE has gained popularity among policy-makers and private sectors in recent years. The search for novel applications of CE has intensified over the past years, making it influential in the body of literature. Because of its consistency in citation analysis, the *Web of Science* database was selected to understand systematically among the recognized journals on how digital solutions in CE has transformed the waste sector to contribute to the UN SDGS.

When being retrieved on 03 February 2022, about 100 articles related to "digital solutions" using keywords such as "waste recovery" and "resource recovery" were analyzed. Afterward, 80 articles were retrieved using keywords such as "circular economy", "smart city", "recycling", and "sustainability". The paradigm used in this study was digitalization-driven solutions such as artificial intelligence (AI).

An increasing interest to the CE paradigm has been indicated in its application in the waste sector for resource recovery recently. This is reflected by the increasing number of CE and/or waste recycling-related publications in the body of knowledge between 1980 and 2021 (Fig. S5). The cumulative number of publications in the same database (1980–2021) significantly rose to 52,441 articles. This reveals seminal approaches in tackling the waste problem, particularly non-biodegradable waste.

3. Results and discussion

3.1. Limitations of waste management in Moscow (Russia)

Presently, waste management practices in Russia are resource-inefficient and aggravated by the malfunctioning of local waste management system for being intensive capital and due to a lack of regular waste collection and disposal services. The lack of an integrated infrastructure for waste management system makes it difficult to plan and manage MSW. The economic incentives for residents to carry out waste recycling are inadequate (Danilina et al., 2020). The low cost of waste disposal distorts incentives for municipalities when selecting either landfilling or recycling. Moscow encounters unprecedented pressures, as its population increases, while its infrastructure systems are stretched.

In recent years, cities in Russia could not collect and dispose of the MSW with limited resources. Traditionally, waste management consumes a lion share of public budget that includes equipment, infrastructure, and manpower costs. Although public service for waste management ranges between 80 and 90% of the MSWM budget for collection costs alone, there is still 40% of the waste uncollected, while only a half of cities' inhabitants is served by the service (Premakumara et al., 2014). As a result, a substantial part of the MSW remains unattended due to inadequate service coverage by the municipalities, obsolete infrastructure, and operational inefficiencies of waste collection services. Hence, optimizing collection services yields large savings of government budget (Yousefi et al., 2021b).

Currently, Moscow adopts open dumping system for the disposal of their MSW (Fig. 4). This causes bad odors and poses adverse implications on public health and the environment. Only a few cities adopt controlled landfills, while so far no city has introduced sanitary landfills (Yousefi et al., 2021a). Consequently, their digestive cells are filled with unsorted waste and a high amount of landfill leachate is generated during rainy seasons. This end-pipe approach results in leachate collection and treatment systems that contaminate the surrounding environment through CH_4 emission into the atmosphere and leachate infiltration into the underlying groundwater, leading to secondary pollution. It is estimated that in 2020, CO_2 and CH_4 emitted from the landfilled MSW were 63 and 32%, respectively, of the country's total GHG emission (Analytical Center for Government of the Russian Federation, 2020b).

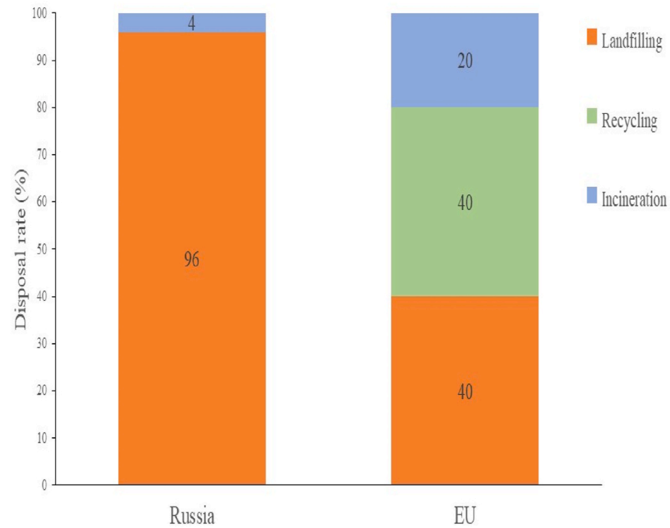

Fig. 4. Disposal method of waste in Russia.
(Source: Ministry of Natural Resources of Russia, 2020)

In Russia, the management of MSW is regulated by the Federal Law No. 89-FZ dated 24 June 1998 "On the Production and Consumption Waste". By the law, municipalities are responsible for providing public with urban cleaning service and MSWM such as waste collection, transportation and treatment (Fig. 5). However, waste treatment is affected by public participation and environmental awareness.This trend will continue into the next decade as the country's urban policy-making is based on command and control in a free-wheeling market economy. As an economic growth without including socio-environmental aspects can lead to skewed growth and environmental impacts, this presents challenges for government to balance between environmental protection and economic growth without sacrificing either of the two in pursuing the 2030 UN Agenda (Symeonides et al., 2019).

The UN's Agenda applies to the country's capital to contribute its part to the SDGs by taking into account socio-economic and environmental aspects of its sustainability paths to the waste sector (Fig. S6). A sustainable Moscow has to be progressive, innovative, open, and livable for all with a high quality of life and effective environmental protection. To implement an inclusive Moscow in line with the 2030 UN Agenda, the capital needs to contribute to climate change mitigation by strengthening its waste management system to respond to the Covid-19 global pandemic. To sustain the MSWM, the development path has to adopt digital technologies (Allegrini et al., 2015).

For this purpose, Moscow needs to undertake the paradigm of waste management from being a problem into being a resource. What the city would today define as waste needs to be reused, transmuted into resources. The problem is how to avoid, minimize, reuse, and recycle the unused waste. Climate change mitigation needs to become a driving force that enhances energy conversion from the landfilled MSW, a source of GHG emissions. For example, the CH_4 emitted from landfilled MSW may be harnessed as renewable energy. The electricity, converted from the landfill gas (LFG), would minimize its dependence on fossil fuels and reduce GHG emissions, of which the carbon emissions may be traded to protect the environment in the long-term (Kurniawan et al., 2021b).

As a key link in the development of smart city, proper waste management is essential. However, an effective waste management in

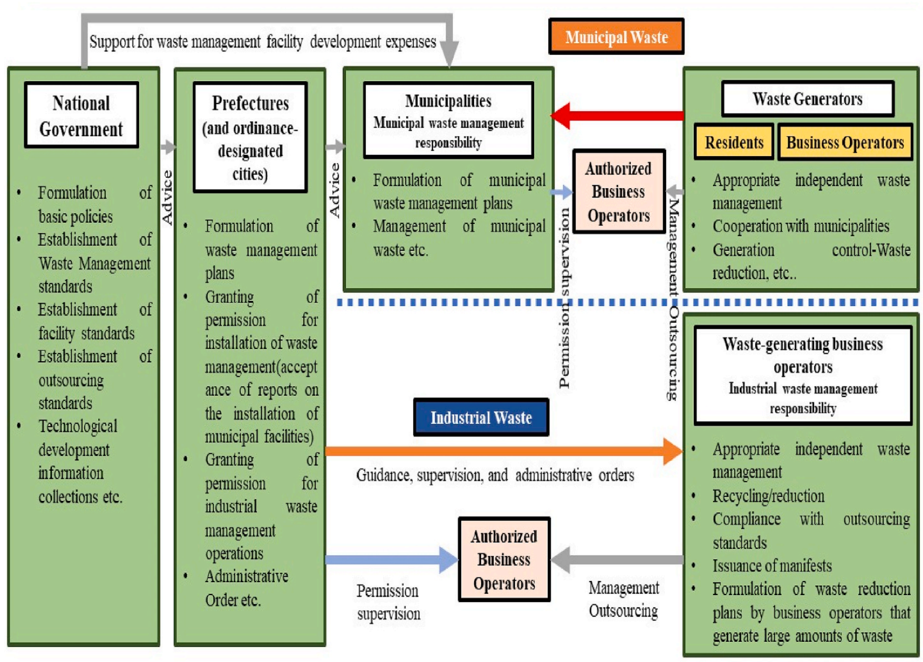

Fig. 5. Relationship between central authority and municipalities in waste management.

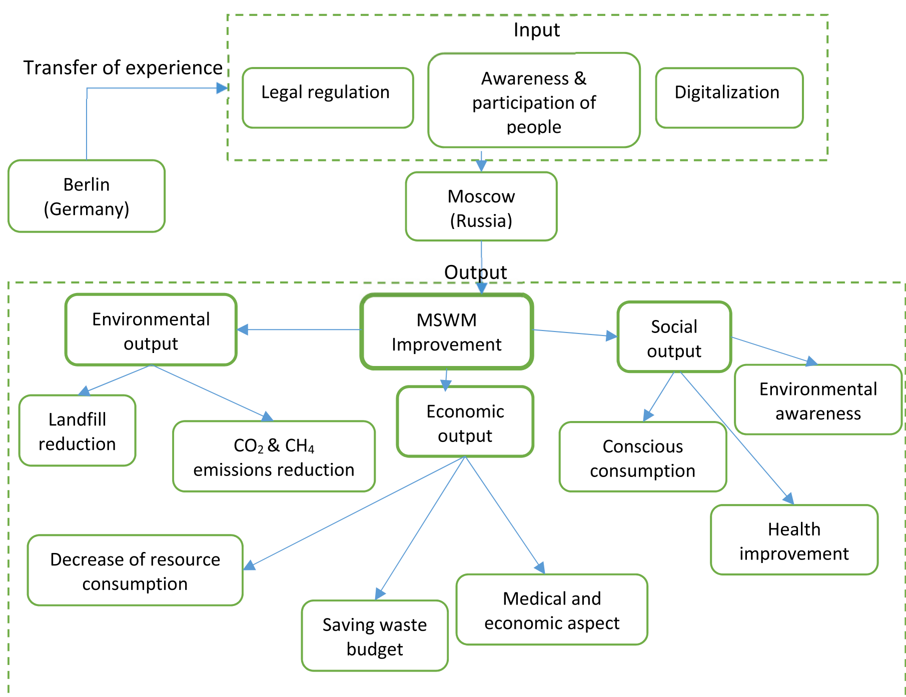

Fig. 6. Conceptual framework **of** Berlin-Moscow cooperation in waste sector.

Moscow is costly, taking a lion's share of municipal budgets for monitoring the waste from its generation, collection, and transportation to its disposal. On an average, MSW management accounts for 80% of the capital's municipal budget (Loizia et al., 2019). Although waste management in Russia is under the jurisdiction of central authority, it is governed by multiple lines of responsibility. Hence, various entities have the same right to enter into individual agreements with collection service providers for waste aggregation services. As there is no single entity to enforce and monitor the national waste management strategy, competing priorities, limited resources, and capacities in planning make local waste management become complicated. As a result, in recent years Moscow has struggled how to operate this essential public service efficiently (Gong et al., 2020).

The Russian capital also encounters various barriers to improve its MSWM such as an undefined system of waste ownership and unclear allocation of responsibilities, the lack of participation by private sector in the waste industry, and the absence of economic incentives for recycling the MSW. Hence, waste management is often neglected in its urban development. The magnitude of the problem becomes increasingly important due to the existence of new materials with a long decomposition period and multi-component objects in their composition (Anagnostopoulos et al., 2015).

The underlying problem in the present waste management is that Moscow residents do not have a strong culture of waste separation and/or waste recycling. In fact, the residents of the capital themselves transfer the waste to the collection points, which is further transported to the refuse transfer stations by private waste collectors. Due to the absence of organized system for separating non-organic waste at source, only 27 million or 19% of the population have access to separate waste collection systems (Vardopoulos et al., 2021). The state-owned waste management practices do not provide economic incentives for reusing recoverable resources. The city's waste management infrastructure is only suitable for easily sorted waste such as plastics, containers, and metals. Although 40–60% are valuable raw materials suitable for processing, only 5% of 70 million Mt of the waste is recycled annually (Cheng and Hu, 2010). The remaining waste is almost completely sent to landfills (Fig. 7). There are about 15,000 landfills nationwide and ten incinerators in Russia (Analytical Center for the Government of the Russian Federation, 2020b).

Such recycled trash is an additional resource to generate raw materials for the city's economy. Not only recycling reduces the quantity of waste disposal into landfills, but also returns approximately 380 million Mt of valuable materials for CE (Kaza et al., 2018), eliminating the pressure to extract virgin materials to be used for manufacturing. Therefore, the practice of discarding unrecycled MSW in landfills results in the irretrievable loss of scarce and valuable materials such as metals and glasses.

Because of the absence of recycling initiatives and less community participation, informal workers (scavengers) are involved in waste recycling to extract secondary raw materials. Instead of promoting waste recycling through scavengers, this should be institutionalized by the municipality. Due to their involvement, the cost for waste processing and treatment is relatively high for both consumers and municipality. The recycling cost ranges from €100 to €250 per tonne (Kaza et al., 2018). This makes waste recycling become difficult and scarcely treated.

When being compared to Berlin that has recovered up to 60% of its MSW, Moscow's waste recovery rate is almost non-existent (Fig. 4). Consequently, the city lacks of recyclable raw materials such as glass and metals because they are sunk in its landfills annually. The materials account for over 40% of the waste. The non-existence of waste recycling results in the annual forgone benefits of over RUB 68 billion (US$ 0.91 billion) (Elagina, 2021).

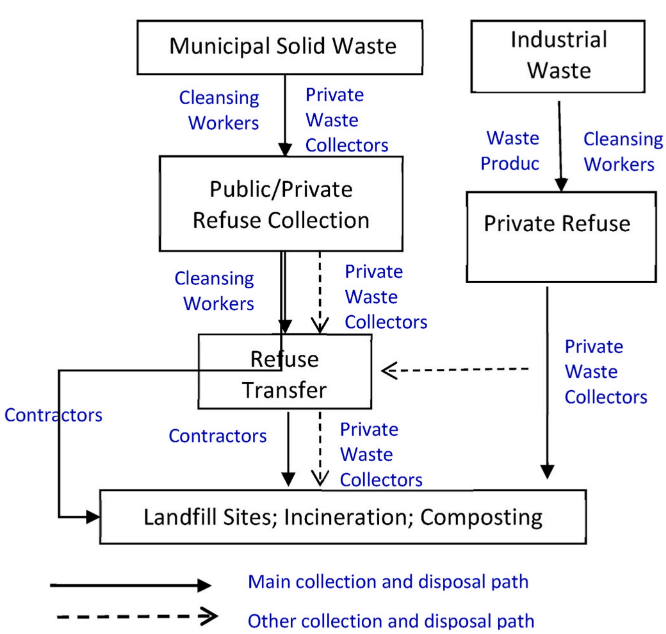

Fig. 7. Mechanisms of waste collection in Moscow.

On the other hand, an increasing recycling returns the materials to production circuit and lower the quantity of waste disposal into local landfills. Their sale would earn about US$ 31 billion of additional revenue, while reducing GHG emissions by 270 million Mt of $CO_{2\text{-eq}}$ annually (Mingaleva et al., 2020). Unless immediately tackled, improper waste management could increase GHG emissions, which contribute to climate change. Therefore, implementing ISWM is mandatory to reduce the environmental impacts.

As most of the waste is disposed of in landfills, their number grows. However, they still lack of the capability of waste processing. The majority of landfills are also obsolete in terms of technology. The deteriorating disposal infrastructures have to absorb vast amount of unrecycled waste. Hence, the existing landfills reach their capacity limits much earlier so that they cannot accommodate the growing volume of waste from time to time (Zhu et al., 2021).

Additionally, 30% of the capital's existing landfills does not meet the international standards of construction and design (Wang et al., 2015). They are not sufficiently equipped to protect the underlying groundwater from leachate infiltration. Therefore, they are not professionally operated. Eventually, this results in environmental challenges such as bad odors, groundwater pollution, and the release of toxic gasses, which poses serious threats to public health. This impact often leads to additional government expenditures during disease outbreaks. Operating such disposal infrastructure will eventually result in damaging environmental implications. This reveals that the landfills no longer meet the needs of the municipality for adequate and sustainable waste disposal (Azevedo et al., 2021).

Other factors include insufficient management of hazardous waste and a lack of market access and incentives for the MSWM. Private sectors, which possess the required technological capabilities to tackle the complex waste management problems, have limited access to market. They also do not have incentives to modernize and build new infrastructures for MSWM in the cities (Zorpas, 2020). For this reason, private sectors need to work with local municipality and authority to find appropriate solutions.

Current situation with local MSW management has escalated with ongoing Covid-19 global pandemic recently, as the composition of waste has changed significantly. The quantity of organic waste such as food has increased, while there is less recyclable fraction. Due to the increasing number of home deliveries to local residents, there is more non-recyclable composite packaging. For this reason, the waste sector requires systemic reforms to improve its resource efficiency (Berg et al., 2020).

The existing waste management system needs to be promoted toward CE as Moscow's land supply is not limitless for landfills. Transforming the waste sector needs not only technological changes and economic incentives, but also a change in consumers behaviors on their consumption. Public campaigns are important tools to reform the waste sector. Placing sorting stations across landfills may provide effective and accessible recycling processes (Ranta et al., 2021).

As MSWM is a multi-participation process, local municipality alone cannot solve all the problems. Stakeholders need to be involved in transforming the capital's waste sector. The establishment of a modern waste management system requires capital expenditures. Achieving a 45% of recovery rate would require USD 2.4 billion of investment. This reduces 30% of demand for new landfill capacity, while generating USD 2.4 billion of revenues from the recovered materials within 5 years (Santti et al., 2020).

In the next 10–15 years, Moscow needs to make a transition from waste disposal in landfills to waste recycling and recovery. To promote a balanced waste management system, it is necessary to set up long-term goals, which promote an efficient use of material. If the MSWM in Moscow modernized the collection, transportation and disposal infrastructure, it could attain eco-friendly and safe waste management by 2025 through recycling technology. The capital requires a capital investment of USD 53 billion to attain a 40% level of recycling and recovery (Kaza et al., 2018). Yet, the amount of recycled waste remains at 5% of the total MSW volume. Waste treatment enables the capital to lessen the investment necessary to build recycling facilities and lower operational costs for automation. The expenses of manufacturing, operation and maintenance of automatic robots are about 75% of the manpowers' cost essential to accomplish the same tasks on a five-year duration (Danilina et al., 2020).

To be effective, the reformation of the waste sector in Moscow requires a monitoring to achieve the targets and introduces new economic and institutional mechanisms through legislations and the authorization of a single government agency to be responsible for this goal. If implemented, there are incentives for industries to integrate waste recycling into supply chains (Fig. S7) (Wang et al., 2018).

Recycling a mixed waste stream is simple, as it needs minimum waste treatment to recycle waste with any composition. If preliminary sorting is done by consumers, recycling waste is efficient at collection centers. Only the recycled portion is transferred to the recycling facility. The end-product of a recycled waste stream can function as an intermediate input material for generating components that industries need to manufacture their products. Their example includes glass waste that has been sorted out according to its color as well as plastic bottles that have been compacted (Wang et al., 2016).

3.2. Lessons drawn from Berlin's successful experiences in MSW management

As urbanization, industrialization, and population grow and move to urban cities, environmental pressures increases. While they grow, so does their contribution of carbon emissions. Utilities (waste, water, and energy) are essential infrastructures in smart cities to enhance their service quality. For this reason, technology has become one of the most promising solutions to maximize existing infrastructure, reduce environmental impacts, and efficiently allocate resources for public benefits. Although technology alone cannot deal with inadequate infrastructure investment, they can help cities add new capabilities to utilities service. As the IoT enables a connection between millions of devices and sensors, by capitalizing on the benefits provided by the IoT, utilities services could be transformed to help cities become cleaner and healthier, while tackling sustainability goals (Berg et al., 2020).

In recent years, smart cities have increasingly resonated with urban residents to respond to their needs effectively and dynamically. As a smart city, Berlin has added digital solutions to its existing urban systems, making it feasible to achieve more results with less resources (Azevedo et al., 2021). Integrated applications position real-time and clear information into operators to make right decisions. Real-time data gives Berliners the ability to understand how demand patterns change and respond fast to them at low cost. A variety of apps is available to make the German capital efficient and productive.

Digital solutions contribute less waste and promote social connectedness. If cities function efficiently, inhabitants are more productive for doing business. This is attributed to the fact that Berlin has one of the most advanced waste management after following a long path to build its current waste management system. The German capital took 30 years to develop its advanced waste management system after reunification in 1990. This does not imply that another city needs to spend such a long time to achieve a comparable level of development (German Federal Government, 2016).

Berlin also has been successful in recycling its waste by using appropriate technology and/or policies (Fig. 8). The city aims at producing zero emissions of GHG by 2050 and decoupling economic growth from resource use. For this purpose, the waste management function is divided between Berliner Stadtreinigung (BSR) and Alba, municipal and private operators, respectively. Annually the city generates almost 1.4 million Mt of MSW. Over 60% is collected and sorted out (Neligan, 2018). With plant's capacity of 225,000 tons, the sorting plant in

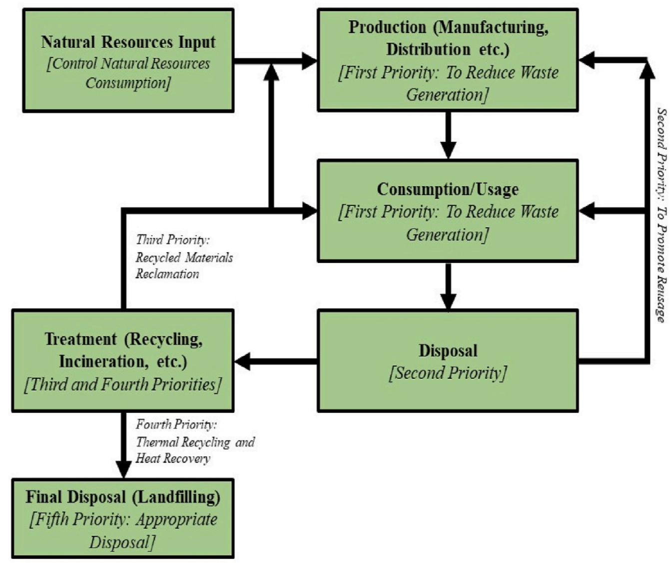

Fig. 8. Mechanisms of waste management in Berlin.

Neukölln, built by the BSR, compresses and resells waste papers with various qualities. Its recycling level has been stable over 93% since 2000, as producers are responsible for waste recycling (Neligan, 2018).

The city implements a comprehensive strategy on resource efficiency such as German Sustainable Development Strategy (GSDS) and the German Resource Efficiency Program (GREP) (Ferrari et al., 2020). The former policy aims at doubling raw material productivity, while the latter improves resource efficiency. Through sound policies and regulations, Berlin has encouraged people to reduce waste by consuming less materials or avoiding the use of certain materials. To improve the waste management tools, German government promotes policy and regulation in MSWM from national level by exerting pressure on waste producers. For this purpose, legislations and regulations are used to guarantee the implementation of waste management initiatives and penalize the environmentally harmful practices simultaneously (Zhang et al., 2010).

One corresponding legislation is the German Packaging Act (*Verpackungsgesetz*). The 1991 Act played roles in changing the waste management system by supporting design for recycling by offering discounts on recycling fee that has to be paid for every package sold. Before 1991, packaging materials accounted for a half of household waste that put serious strains on local utility. After 1991, government transferred the responsibility for waste collection and disposal to producers and the importers of goods and switched to a new system. Packaging producers have to pay fees for its disposal. The fee is used to pay recycling industry to recycle their packaging waste. Monitoring and documentation necessary for implementing the acts rely on digital technologies such as AI or ML (Hollins et al., 2017).

A few digital technologies used in the waste management sector include a digital system named MOBA (Mobile Automation). Through cloud computing, the digital solution is responsible for tracking, container and customer management, navigation, and route planning. Other digital solutions are *Enway* and *Stadtreinigung Hamburg* systems. The first is autonomous, self-driving sweeping vehicles that perform cleaning tasks in public areas, while the latter is *AI* image-based classification for illegal littering. Residents take the images of illegal littering with their smartphones. The software classifies the images and redirects them to appropriate agents (Marsal-Llacuna and Segal, 2016). ML also gains popularity for automating the waste classification process.

The technologies have been used to control urban infrastructure systems in waste management (Fig. S8). They include digital tracking and payment gate for waste disposal and optimizing waste collection routes. Digital tracking and payment for waste disposal charge users exactly for the amount and type of trash they throw away. Digitally enabled 'PAYT' systems include feedback via mobile apps delivered to users to increase people awareness and reduce waste. The digital tools can help residents reduce unrecycled waste (Okorie et al., 2018). There is a potential reduction of unrecycled waste generated between 30 and 130 kg per person annually. Hence, Berlin introduces an RFID-based PAYT system in apartment blocks and sends residents electronic update about their consumption level.

Recyclable materials from household waste and waste packaging are collected in a combined recycling waste bin, of which thousands RFID trackers have been installed. As the smart bins that act as Wi-Fi hotspots are equipped with sensors, the discarded waste from the bins is continuously monitored by the sensors that inform the used volume of each compartment in real-time. Not only high-resolution cameras and sensors are used to separate recyclable from the non-recyclable fraction, but thermal imaging is also applied to scan certain vectors for classification purposes. This efficiently separates the biodegradable from non-biodegradable waste (Liang et al., 2022).

Trash bins with automatic sorting identify the composition of secondary raw materials using sensors and separate them on a conveyor belt based on image recognition. The sensors, connected by high-speed networks over internet, take constant readings of variables such as type, weight, and composition of the waste and put the information at the fingertips of those, who need it (Madhav et al., 2021). The sensors also regularly provide instant updates on the status of the trash bins with real-time feedback of data through smartphone apps about their waste at homes, while maintaining proper management of the trash bins.

The use of sensors inside the trash bin not only measures the trash volume of the container, but also enables time-detection when waste collection is required (Ordieres-Meré et al., 2020). After storing and processing them in an IoT platform, the waste data are transmitted to an online platform through internet, where citizens can access and check the availability of the public waste bins scattered citywide through the Web or a mobile app. Residents may engage with smart city ecosystems using their mobile devices. Pairing devices and data with the city's physical infrastructure and services can reduce the costs and improve sustainability without requiring human intervention (Fig. S9) (Ivanova, 2020).

Digital solutions can facilitate communication between waste management companies with their customers about pick-up schedule, price inquiry, and documentations. For communication, people use cloud servers that collect data about the conditions of the waste. The data are sent to the companies and their customers via mobile apps, which display information on the cost, the schedule of waste collection, and other events. The companies also provide data on collection stations (Kang et al., 2020).

This intelligent solution can also be evolved by adding new facilities that can bring interactions with the control system to calculate the best route with optimized collection routes (Fig. S9). The use of sensors inside trash bins directs the routes of driverless trucks. This application keeps the trucks from traveling to collect trash bins with little waste volume. This not only maximizes pick up time and enhance efficiency with a lower cost of driverless trucks up to 75%, but also reduces truck fleets and fuel consumption by keeping short routes from collection points to disposal sites, thus decreasing GHG emissions from waste collection vehicles (Komyshova et al., 2020).

While protecting labourers from the toxic nature of non-biodegradable wastes that can cause long-term effects on their health, the automatic separation into different recyclable waste is carried out efficiently using sensor-controlled plants (Goh et al., 2022). The utilization of digital solutions enables infrastructure service providers to maintain their performance capabilities, improve the quality of their services for their customers, and add productivity by linking low-cost technologies, thus achieving a sustainable reduction in their consumption of resources (Zhu et al., 2020a).

The creation of smart trash bin and the use of waste management system for evaluation, demonstration, and validation show that the city's smart system can efficiently transform how to better deal with trash and optimize material resources in terms of resource management, as valuable components are extracted from the remaining wastes. Resource recovery and recycling of non-biodegradable wastes are substantially enhanced by including classification of metallic and non-metallic fractions from the identified materials (Vilve et al., 2010).

Smart supply and disposal means make a sustainability transition from a throw-away system to a resource-optimized recycling system. A complete systems for the supply of resources and the disposal of waste are involved. With innovative solutions in recycling (waste utilization), upcycling (creative reuse of waste), and urban mining (reclaiming compounds from waste), the systems can be developed for reclaiming critical and rare raw materials (Kurniawan et al., 2021a). Robotic deployment to the best reasonable extent could reduce the volume of unrecycled waste per capita by 20% (Sarc et al., 2019).

In addition to the 1991 German Packaging Act, the city's waste management system is regulated according to the Act on "Closed Cycle of Materials". The 1994 Law aims at reducing waste incineration through "zero waste" and recycling to achieve an almost complete utilization of MSW. So far, Berlin's experience shows that an effective waste management requires a well-developed infrastructure such as containers for various waste and local waste management companies. There is high fine for disposing of waste in unauthorized places. This policy aims at reducing the amount of waste generated and increasing the volume of waste recycling (Kurniawan et al., 2021b). German companies reduce the consumption of valuable resources by improving material life cycle and the eco-design of products and using resources more than once through reuse and recycle. The companies follows the universal hierarchy of waste management (Fig. S10) (Kunkel and Matthess, 2020).

Apart from digital solutions, Berlin uses policy instruments such as economic instruments (Table S1). Waste charging policy is applied to achieve waste prevention/reduction. From international perspectives, this policy enables people to change their consumptive behavior. Residents pay less if they throw less. The policy ties waste charge to the cost of collection and disposal, providing incentives on waste generators to reduce waste through changes in purchasing styles and reuse of containers. What cannot be reused directly, but can be recycled or recovered such as paper, plastic and mental, should be maximized for its value through recycling (Kurniawan et al., 2021c).

Berlin charges every household a waste disposal fee based on the number and size of their trash bins, and the frequency of waste collection service (Fig. S11). Instead of a fixed monthly fee for waste collection, residents pay a fixed amount, which corresponds with the quantity of the MSW they generated. The fee charged to households in Berlin depends on the size of the waste container. If the waste disposal fees are imposed, this promotes a responsible waste management, while people have incentives to change their consumptive behaviors, thus increasing public participation and enhancing their environmental awareness. Due to the economic instruments, Berlin achieved a substantial waste reduction in 2020. This suggests that the waste management in Berlin is effective to facilitate the MSW transfer for recycling and reuse (Rajput and Singh, 2020).

3.3. Moving towards a digitalization-based MSWM system in Moscow

Moscow aims to harness the opportunities offered by digitalization by 2023. Residents will have access to advanced digital infrastructure. With 5G and sensors as the backbone of their communications infrastructure, local industry and public sector have the required conditions for promoting cooperation and enhanced efficiency (Kurniawan et al., 2021d).

Digitalization transforms the world on unprecedented scale and speed and presents substantial market opportunities by injecting new technology directly into the lives of urban residents. Through digitalization, recent advances in environmental technology have facilitated convenient service delivery to urban society. It is a driving force to change the traditional paradigm of waste management, which is neither sustainable nor reliable. Introducing digitalization into MSW management in Moscow is the first step. However, applying it to maximize its effects on the environment, society and economy is completely different. Therefore, digital solutions have not brought an immediate transformation in the first year of its implementation (Van Ewijk and Stegemann, 2016).

Digital transformation takes time for smart cities because the utilization of digital infrastructures in waste management requires strategic planning to smoothen the development process. This can be challenging for bureaucrats because applying digitalization to transform waste sector requires new paradigms of governance (Scherbakova and Khaikin, 2019). Technology is only effective when the municipality puts it to work for the government and society.

Smart waste management involves ICT to make critical decisions from waste generation and collection to its transportation and disposal. Previously Berlin also has experienced the same situation. Once digital technologies are introduced in its waste management infrastructure, Moscow still has to develop the required capabilities before the residents can reap the benefits of digitalization with respect to productivity and cost-efficiency (Vasilyev and Bykov, 2015).

Other benefits of smart waste management include real time information on the state of the trash bins, effective deployment of driverless trucks based on actual needs, cost reduction and resource optimization, less cost for waste collection, less GHG emission, and cleaner cities. It is expected that ICT would promote intelligent management of the services in Moscow (Khan et al., 2016).

As smart waste management presents automatic and connected systems that provide opportunities in waste collection through route optimization, the reform of MSW management in Moscow may be started from time-efficient waste collection. With a cloud-based waste management, Moscow can handle and manage the MSW practically and efficiently from waste collection points by deploying sensors in trash bins citywide to monitor waste levels in real-time and sending alerts to identify appropriate collection methods based on waste volume and its types (Vazquez et al., 2021).

After building an IoT platform to monitor and control applications via the internet, the sensor that translates raw data into alert subsequently upload the waste status to the cloud. Additionally, the sensor can detect if there is a person close to the bin for disposing of the waste and a lid will open automatically for him to throw away the waste. This automatic opening and closing of the lid is essential to prevent the waste from being exposed to the sunlight. Otherwise, the waste will be decomposed and eventually, bad odor is released into the environment (Vergara and Tchobanoglous, 2012).

As an efficient waste collection promotes better public health and environmental friendliness, waste bins are connected to the cloud and data are stored in the cloud in real time. The status of trash bins is updated periodically to stakeholders with respect to the type of waste, its quantity, and collection time. If there is not enough waste for collection service, no visit service by garbage trucks will occur. It is also possible to choose cost-effective routes and select their path for waste collection, saving fuel for optimum resource management (Vukovic and Pobedinsky, 2019).

Relevant stakeholders can access and analyze a large amount of data from the cloud (Fig. S12). The cloud enables them to analyze what type of the waste and its magnitude. This automated data acquisition and communication enables better arrangements to minimize waste generation and improve its recycling efficiency. Eventually, the digitalization of waste collection makes the waste sector become more efficient, more responsive, safer, and more sustainable. By using the sensors installed in trash bins, the digitization of waste collection provides benefits such as cost optimization and resource recovery, full control of the operations and efficiency, flexibility, easy adaptation of the services to targeted interventions, and a fast application of "PAYT" systems (Wilt and Berg, 2017).

Sensor data and high-tech command centers revolutionized the way in managing complex operations and automating infrastructure systems of waste management. A river of data is continuously fed by sensors embedded throughout physical environment. The sensors capture troves of data in real time and feed it into analytics systems that run complex operations and infrastructure in Moscow. This makes instant remote adjustments without human intervention. As millions of users digest the data to make appropriate decisions, this will make Moscow become productive and responsive because energy, resources, and investment are consumed efficiently (Romanyuk et al., 2021).

After developing digital solutions for waste reduction and minimization, Moscow needs to focus on the waste recycling of non-biodegradable waste. By processing parts of a product or the whole product into materials such as plastics, metals, and glass to become secondary resources, the city can promote waste reduction, achieving zero-waste (Wang et al., 2018). If recycled content and recyclability play roles in choosing a product, this can leverage the use of recyclate and design for recyclability on the producers' side. Hence, the recyclers need to improve the sourcing of waste streams through digital platforms (Van den Berg, 2016). As traditional recycling reaches the limits of what recyclers can do, digital solutions could further minimize the volume of unrecycled non-biodegradable waste.

Search and transaction costs can also be lowered drastically, improving the price competitiveness of recycled materials, as compared to that of virgin materials. In addition, fast and transparent data about the quantity of suitable waste streams facilitate stable recycling markets. Digitalization can substantially optimize waste collection and recycling by utilizing technology and data that make waste industry become more efficient, more responsive, and more sustainable (Yang et al., 2016).

The activities can be undertaken using mobile applications (*apps*) to connect waste generators/sellers and waste buyers in a virtual marketplace. In Yogyakarta (Indonesia), *Rapel* apps has been used to facilitate online transactions (Kurniawan et al., 2022c). The lack of knowledge or the distrust in recycled materials could be addressed by the platforms, as digital tools for materials recycling exist. Digital solutions can prevent monopoly and platform businesses where they are not beneficial to the markets. The transition towards the digitalization of MSW management create 5,000 new jobs of waste sellers. This not only reduces the city's unemployment rate, but also facilitate the resource recovery of non-biodegradable waste (Kurniawan et al., 2011).

Although digital technologies eliminate administrative and field jobs, they create maintenance roles and temporary installation jobs. This can bring positive impacts by creating efficient mechanisms for hiring and drawing unemployed people into existing workforces. Digital solutions do not substitute people's jobs, but make waste recycling markets become more efficient (Schalkwyk et al., 2018). To rapidly integrate them with the capital's waste management routes, automatic robots are also used to complement the manual labor system by reducing the required time for manual intervention in waste segregation. Their capacity to navigate waste segregation efficiently attains the same result as that of traditional waste collection. This decreases the need of manpower for waste segregation and recycling.

Normally, the macro-sorting of waste materials requires extensive manual labour. The existence of robotics for waste sorting elevates the automated waste recycling to the next level. Deep neural waste identification coupled with autonomous robots acts as a driverless waste pick up system. Moving towards digitalization of waste recycling could improve the efficiency of waste recycling from process automation and quality control to e-commerce platforms. For this purpose, technological intervention facilitates the delivery of non-biodegradable waste to well-equipped recycling centers. As a result, the better the waste is sorted out, the better it is recycled, the less ends up in landfills (Weber et al., 2020).

For an efficient waste collection, Moscow also applies automated solutions such as Fandomats to collect PET bottles and aluminum cans.

To enable a proper waste management, the smart bins are equipped with automatic sorting by fractions at every collection point (Kurniawan et al., 2013). The bins are automatic machines for receiving secondary raw materials in a suitable form for processing. Installing Fandomat in popular places helps municipality to involve public in the waste separation.

Segregation is a necessary step for recycling waste. The degree of waste segregation affects the efficacy of subsequent steps in waste recycling. The most simple segregation is sorting out the entire waste stream into organic biodegradable and non-biodegradable fractions, and then separating it between toxic and hazardous one. The technologies employed vary based on the type of materials (plastics, metals, or glass). Each requires unique treatments and has different market characteristics. Therefore, new markets for their recycling/recyclable materials need to be created so that they could return to the manufacturing circle for further use, promoting CE (Simatele and Etambakonga, 2015).

Based on Berlin's experience in implementing extended producer responsibility (EPR), suppliers are required to arrange the safe recovery of their end-products (Schulze, 2013). Applying EPR in local settings not only stimulates the recovery of the most important MSW fractions and encourages new capital investments, but also makes the waste management system become efficient (Wang and Li, 2021). An authorized government agency may oversee this responsibility by comparing the products that enter the market versus those that exit. When the producer's stranded costs for getting recyclable fractions become consumers' responsibility, the concept of the "polluter pays" principle is introduced in the manufacturing supply chain (Zhao et al., 2011, 2020).

Traditionally, it is feasible to extract 5–20 various fractions from a mixed waste stream using conventional and/or automatic sorting. If Moscow reforms its MSW management policy by applying digital technologies, by 2030 the Russian capital could recover up to 45% of its waste or about 200 million Mt of the MSW will be recovered to raw materials and energy (Sharma et al., 2020). As the implications, this will reduce demand for new landfills' capacity by 30%. Additionally, this requires capital investment about Euro 40 billion and generates additional revenue of Euro 2 billion from recoverable fractions (Schwanholz and Leipold, 2020). This approach could be replicated worldwide to resist the pressure of resources consumption, deliver socio-economic and environmental benefits, and protect the environment for current and future generations (Zheng et al., 2016).

In spite of promising projection, there are challenges in Moscow to achieve a sustainable and smart waste management. They include financial supports such as low investment in MSWM and institutional capacities such as a lack of coordination among municipality's agencies, and social support such as public participation. To address this, Moscow needs to develop legislations and regulatory frameworks for MSWM, conduct separate collection and recycling system, while incorporating digital technologies into the waste management system (Zhou et al., 2015).

Becoming a smart city is not a goal for Moscow, but a means to a final destination. By optimizing the configurations for macro-waste sorting systems with autonomous robots, Moscow can respond more effectively and dynamically to the needs and demands of its urban residents. By using digital technology and data as tools to make appropriate decisions and deliver a better quality of life, Moscow can improve the outcomes for residents and involve public participation in shaping the city as their home.

3.4. Implications of digitalization on waste recycling practices

Rebuilding global economy in a post-Covid-19 era has never been more urgent. All around the world, countries have encountered socio-economic fallout from the pandemic since 2020. The IMF estimated that the global GDP shrank an unprecedented 3.3% in 2020, the world's worst recession since the 1929 Great Depression (Analytical Center for the Government of the Russian Federation, 2020b). Recovery is diverse across and within countries in the Asia Pacific region, creating a large gap in living standards among its inhabitants.

In the 4th Industrial Revolution (4IR) era, the opportunities that digitalization offers for accelerating sustainable development are endless (Fig. S13). There are hardly any industrial products, in which digital solutions are not involved. With digitalization, the world has experienced technological advances that benefit the nexus of society, environment, and economy. Having been benefited from the advances in ML, cloud computing, and big data, AI leads a revolution in information technology and fosters sustainability transitions in a broad range of application realms (Kurniawan et al., 2014). By providing round-the-clock support, the digital transformation not only has brought cutting-edge solutions to make processes more efficient, faster, and more sustainable, but also created new markets that offer inclusive approaches for connectivity among communities from cities to remote areas. Whether in business or society, digital solutions have permeated and changed our daily lives on unprecedented scale and speed with ever-increasing connectivity (Sarc et al., 2019).

By 2050, over two-third of the world's population will be living in urban cities (Ferrari et al., 2020). This offers the world with opportunities to develop new approaches for a sustainable consumption of resource through digitalization. Amid the pandemic, digitalization has the potential not only to transform urban waste management practices for a better sorting and recycling process, but also to tackle a critical supply of scarce and valuable raw materials caused by industrialization. Retrieving information about the sorted common waste from different waste streams into an almost pure quality could be attained on handheld devices. With data scientists, cities may implement sustainable digital solutions for transforming their waste management industry into digitalization (Abdallah et al., 2020).

Transitioning towards a resource-saving and future-proof economy through digitalization not only alleviates the pressure of resources consumption and delivers environmental and socio-economic benefits, but also protects the environment for current and future generations. Digitalization promotes a resource management across the value chains. Based on IT-based business models, knowledge for correct waste segregation can be provided by using sensors (Antonius and Zorpas, 2019).

In this societal transition towards CE, digitalization integrates circular thinking into various stages of the life-cycle of non-biodegradable waste such as waste electrical and electronic equipment into critical raw materials by linking the digital platform with environmental technologies. Digitalization for waste recycling, which ranges from automation, characterization, and quality control (upstream) to platforms for online transactions (downstream), revolutionizes waste sorting and recycling. Eventually, the digitalization of waste management makes recycling industry become efficient, responsive, and sustainable (Ranta et al., 2021).

How the digitalization retains the value of used materials within CE plays roles in identifying opportunities not only reduces raw material consumption from metals and minimizes GHG emissions, but also conserves critical and rare raw materials. For this reason, the development and applications of resource-saving technologies need to be connected with people (Fig. S14). This includes user interfaces and digital business models in the form of apps, virtual, and augmented reality.

The mobile phone applications (apps) platform presents the recyclability of used materials when their barcodes are scanned to explain how to recycle specific products. A lack of knowledge in the recycled materials could be addressed by digital information. Recyclers could improve the sourcing of waste streams, which can be supported on waste-trading digital platforms such as scrap-metal search. Transaction cost becomes less substantially, improving their price competitiveness, as compared to that of virgin materials and providing fast and transparent information about the quantity of waste streams to create a stable waste recycling industry. Relevant report on the quality of used materials on the platforms and the possibility to compare offers could add value into the information on its quality. The availability of material passports presents reliable and transparent information for the market (Zhu et al., 2020b).

3.5. Perspectives of digitalization in waste management practices

The 4IR involves driverless machines that coordinate production processes by cooperating with people in a structured and intelligent manner. For example, intelligent digitalization contributes to waste management practices by aligning with the 12th UN SDGs "Responsible production and consumption". Intelligent data collection and analysis using AI makes waste recycling process more efficient and faster than manual separation. For example, driverless vehicles receive their commands directly from a computer system about what material needs to be sorted out, recovered, and recycled from trash bins to production lines. Afterward, the robots drive the entire process by themselves in optimizing production processes. By linking production lines with digitalization platforms, intelligent manufacturing sector contributes to the 2030 UN SDGs (Kurniawan and Oliveira, 2014).

As an inteligent solution, AI has the capability of copying the way human brain processes information by mimicking the functions of human mind such as reasoning, problem-solving, and interacting with the environment. To solve the problems, AI deals with processing data, detecting patterns, and generating outputs through algorithms, which systematically and automatically preprocessed data. This ability not only strengthens our abilities in identifying correlations and making recommendations, but also makes lives more practical and convenient (Esmaeilian et al., 2018).

In the IoTs, all devices are capable of interconnecting and communicating with each other over internet. Therefore, the IoT enables business to make it users-friendly for suppliers to connect with the market online and improves automation. When being integrated with IoT, AI becomes powerful by making use of online data and facilitating people to control devices like robots through the internet. While moving around at every collection point and photographing target waste materials, the AI-based robot identifies and carries out separation of the identified materials via its arm-based lift. This represents a viable solution for waste collection with minimum human intervention, as the waste is placed within its platform. After collection, the robot returns to driverless trucks and stores it in their secluded space. A convolutional neural network–based identification system that has been applied for classifying the identified materials yields an almost perfect accuracy. Robotic deployment eventually will propel the world towards autonomous waste collection (Liang et al., 2022).

Unlike the traditional Internet, where the main producers and consumers of data and information are people, in the IoT various objects with different complexities generate and use the largest amount of data and information (Jamasb and Nepal, 2010). The use of robots in waste recycling could make a major contribution to the production of high-quality secondary raw materials from waste for promoting CE. Automating the segregation of waste using the robots can increase the speed of waste separation and reuse of recyclable materials, while reducing waste and minimizing harmful effects to scavengers.

A recycling robot is considered to be the world's first robot-driven waste sorting device with AI. The robot, equipped with computer vision and deep learning algorithms, selects waste fractions from construction and demolition (C&D) waste through visualization tools, the best way for identifying the targets without being lost in their details. A single robotic arm can handle up to four varying fractions with 99% of purity. Although the robot has so far been used for C&D waste only (Li et al., 2021), the combination of autonomous robotics and deep learning for waste collection and separation from waste stream benefits the city's collection centers substantially in terms of time efficiency (Lin et al., 2017).

To increase its efficiency and reduce the cost of waste separation, the robots are used to sort out MSW streams. To effectively manage waste and increase the share of secondary raw materials from the MSW that go for processing, it is necessary to automate and use IoT technologies at all stages from collection to processing. Sorting techniques that do not depend on the physical properties of materials for separation need materials identification (Gubernatorov and Stepanova, 2021).

As the accuracy and sensitivity of the technologies continue to improve, other technologies need to be developed to identify various materials in the waste streams. Although technological solutions alone could not make a leapfrog in the waste recycling industry, they become important to transform the entire value chain from manufacturing to disposal. With their disposal infrastructure, waste recycling industry can add value to the supply chain of waste management by removing more or less precisely sorted material fractions, which can be diverted directly into production lines or sold as raw materials on the market, reducing the amount of waste disposal in landfills (Van Ewijk and Stegemann, 2016).

In addition to algorithms, digital workflows for data acquisition, processing and analysis, and access to quality data are essential. The technology not only facilitates transactions, delivers products and services timely, but also makes customers' payments faster at low-cost. Embracing digitalization enables the waste sector to redefine waste recycling industry by closing the loop of scarce and critical raw materials. This approach is economically attractive, as the involvement of secondary resources in the manufacturing for production can substantially minimize production costs (Voukalli et al., 2021).

3.6. Contribution of digitalization in waste recycling to city's resilience against Covid-19 pandemic

Waste recycling is a top priority for urban cities to reduce MSW. As complete recycling rate is unlikely to be attainable, the market demands digitalization to replace traditional waste recycling. For this reason, recycling technologies have been developed by undertaking a mobile robotic system as an option for classifying non-biodegradable waste at recycling centers. With the MSW charging scheme likely to be carried out later, policy-makers anticipate a strong market demand for cost-effective recycling technologies that can develop recycled materials without lossing their quality and functions.

To transform their economy toward net-zero emission, cities need to use digitalization to harness their growth potential during their transition period due to the Covid-19 global pandemic. The transition in waste sector beyond CO_2 emission reduction builds cities' resilience by strengthening their waste management practices to respond to the pandemic using digitalization (Yousefi et al., 2021a).

On-going global pandemic represents a turning point for Moscow to evolve as a smart city. Digitalization in waste management offers an unrivaled opportunity to better deal with its adverse impacts by developing new platforms such as integrated command and control centers that promote cooperation among on-duty officers and their timely response to urban waste services through forecasting, prediction, automation, and hotspots identification. In the long-term, this technological intervention will contribute to the Russian capital's enhanced resilience through adaptation ability and recovery towards sustainability (Fu et al., 2021a). According to the McKinsey report "Digital Russia: New Reality" the volume of Russia's digital economy by 2025 will grow by 200% to RUB 9.6 trillion (US$ 0.13 trillion) (Fedorov and Kuznetsova, 2020). The country has all the prerequisites to achieve the goal of tripling the size of its digital economy by 2025.

The pandemic also presents to the world a game-changing opportunity to put its sustainable development path on digitalization. The increasing demand for scarce raw materials requires an improved efficiency and increasing supply of raw materials. Digital technologies such as AI, IoT, and big data have changed the paradigm of sustainability in waste management practices from 'being a problem' to 'a resource' in the framework of CE (Table S2). To replace traditional linear economy, CE uses fewer resources, while consuming them longer or multiple times. To enable their impacts on society, not only development and investment in AI, but also digital data infrastructures are necessary. Digitalization boosts the transformation towards a more sustainable CE by closing or slowing the material loop and narrowing the loop with increased resource efficiency (Fu et al., 2021b).

As opposed to the linear economy, in which resources are created, used, and disposed, in CE resources are used for as long and as productively as possible. At the end of their useful life, their products and materials are recovered and regenerated. Introducing CE in waste management systems requires adequate valorization and related management schemes that need sophisticated approaches for their implementation (Yigitcanlar and Kamruzzaman, 2018).

4. Conclusions

Urban waste management is a critical issue in Russian Federation. This requires an integrated system approach to deal with it effectively and efficiently. There is a growing need to develop and implement digital technologies in the field of waste recycling such as AI and ML to improve MSWM.

To promote a societal transition, this study has demonstrated that moving towards digitalization of waste collection and recycling could improve the efficiency of solid waste management system from upstream to downstream. With digitalization, the better the waste is sorted out, the better it is recycled, the less ends up in landfills. Urban cities could experience technological advances that benefit their society, environment, and economy in the long-term.

Unlocking digitalization for accelerating a societal transition in the waste recycling industry not only has contributed to the UN's SDGs by 2030, but also has facilitated a transformation towards resource recovery for CE in Moscow amid the Covid-19 global pandemic. Digital technology could minimize the amount of unrecycled MSW, while conserving raw materials and reducing operational cost and GHG emissions. When the recyclables are separated from non-recyclables at sources, unused non-biodegradable waste could be a source of raw materials that reduces the extraction of natural materials. The aspects of cleaner production are relevant to all industry, regardless of type or size.

Globally, the pandemic has accelerated smart cities' development in their transition in the waste sector beyond CO_2 emission reduction. Digitalization has built their resilience by strengthening local waste management practices to respond to the pandemic. This also contributed to their adaptation and mitigation that offer multiple benefits with respect to socio-economic and environmental aspects.

In Moscow, the transition towards the digitalization of waste recycling through informal waste sectors created 5,000 new jobs that reduced the city's unemployment rate through the resource recovery of non-biodegradable waste. The use of robots for waste collection maximized pick up time of driverless trucks and enhanced cost-efficiency with a lower cost of driverless trucks up to 75%. A convolutional neural network–based identification system that has been applied for classifying the identified materials yielded an almost perfect accuracy. A single robotic arm could handle up to four varying fractions of C&D waste with 99% of purity. As implications of the study, robotic deployment reduced the volume of unrecycled waste by 20%. Eventually, the digitalization of waste recycling makes the city's waste sector become more efficient, more responsive, safer, and more sustainable. This approach could be replicated to resist the pressure of resources consumption, deliver socio-economic and environmental benefits, and to protect the environment for current and future generations from climate change impacts.

To support further digitalization, future research work needs to include the limit of robotic arm's payload to enable the collection of large appliances such as freezers. The addition of such non-biodegradable waste can promote the applications of robots worldwide for waste collection purpose.

CRediT authorship contribution statement

Aleksandra Maiurova: Data curation. **Tonni Agustiono Kurniawan:** Supervision, Writing – original draft, Writing – review & editing, Funding acquisition. **Marina Kustikova:** Formal analysis. **Elena Bykovskaia:** Formal analysis. **Mohd Hafiz Dzarfan Othman:** Conceptualization, Validation. **Hui Hwang Goh:** Supervision.

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.

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Appendix A. Supplementary data

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