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Accelerating sustainability transition in St. Petersburg (Russia) through digitalization-based circular economy in waste recycling industry: A strategy to promote carbon neutrality in era of Industry 4.0

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ABSTRACT

Due to industrialization and economic development, urban expansion in St. Petersburg (Russia) has swelled its solid waste generation. The current waste management system does not meet the city's needs. Fundamental changes are required to accelerate its sustainability transition to achieve the 2030 UN's Sustainable Development Goals. This article critically evaluates and analyzes the existing situation of waste management in St. Petersburg and its role in promoting digitalization-based circular economy. Challenges in waste recycling that prevent it from reforming its waste management are identified. Lessons drawn from Taiwan's prowess in resources recovery are presented to inspire a transformation of its waste sector towards a digitalization. The implications of digitalization on the city's waste recycling industry are elaborated. Before applying digitalization, St. Petersburg encountered challenges such as a lack of proper infrastructure in waste management, low public participation and environmental awareness, technological gaps, and insufficient coordination among its institutions. As one of the world's leaders in waste recycling (65%), Taiwan was selected as a role model for St. Petersburg in improving its waste management. The Island's daily per capita rate decreased by 96% to 0.4 kg in 2015. Taiwan also minimized the amount of waste disposal into landfills to less than 2%, while 80% of its industrial waste was recycled. About 33% of annual waste generation in Taiwan was reduced through "Pay-as-you-throw" policy. The average volume of municipal solid waste generation per capita decreased by 20% to 0.91 kg/day. This suggests that moving towards digitalization has minimized the extraction of raw materials through resource recovery. As implications of digitalization in waste management, the consumption of virgin materials could be lowered by 25% in 2030, while a half of greenhouse gas emissions could be avoided. The World Economic Forum estimated that the circular economy could potentially add USD 700 billion in material savings to global economy.

1. Introduction

With its area of 1439 km^2, urban space in St. Petersburg (Russia) is characterized with a high population density (Mingaleva et al., 2020). In 2018, over 75% of its 5.4 million inhabitants lived in urban areas (Chusov et al., 2018). Around 5.4 billion of waste is generated annually, of which about 71 million Mt is MSW with 1.1 kg per capita daily (Nazarova, 2020). With 10% of annual growth rate, about 90% of the MSW is disposed of in open dumps (Schwanholz and Leipold, 2020), while the rest is sorted for recycling. Annually 0.3 million hectare of land is required for expanding landfills (Putinceva et al., 2020).

The pandemic has revealed the potential of digital technology for the country' second largest city, which intensifies its search for a new technology to tackle the MSW. As the current status quo needs to be overhauled with digitalization, integrating information and communications technologies (ICT) represents a solution to develop a smart and sustainable city (Chau et al., 2021). The improvements of urban

Abbreviations: Mt, metric ton.

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List of abbreviations

AI	artificial intelligence
CE	circular economy
EPR	Extended Producer Responsibility
EU	European Union
GDP	gross domestic product
GHG	greenhouse gas emissions
GIS	global information system
ICT	information and communications technologies
IoT	internet of things
IPCC	Intergovernmental Panel on Climate Change
MOEA	Ministry of Environmental Affairs
MSW	municipal solid waste
MSWM	municipal solid waste management
NTW	New Taiwan Dollar
PAYT	pay-as-you-throw
PPP	public-private partnership
PRP	Producer Responsibility Program
RFID	Radio Frequency Identification
RMF	recycling management fund
RFM	Recycling Fund Management
ROC:	Republic of China
RRRA	Resource Recycling and Reuse Act
SDG	sustainable development goals
SSC	smart sustainable city
TEPA	Taiwan Environmental Protection Agency
UN	United Nations
UNFCCC	UN Framework Convention on Climate Change
USD:	United States dollar
VCF	volume-based collection fee
WDA	Waste disposal act
WEF	World Economy Forum
WoS	Web of Sciences
WRCPA	Waste Resource Cycling Promotion Act

infrastructure and life quality can be attained by proper applications of smart technologies (Nguyen et al., 2021).

Preliminary studies on MSW management in St. Petersburg undertaken by Drozhzhin et al. (2019) and Vidiasova and Cronemberger (2020) focused on the readiness of Russian cities to implement 'smart city' concepts. In spite of their novelty, their studies did not address the socio-economic aspects of waste in CE. Their works neither took into account digitalization as a part of solutions in St. Petersburg nor explored intelligent methods for re-use and recycling of waste materials from industries (Abramova, 2021).

To bridge the research gaps, this article reports transition pathways in St. Petersburg's MSWM based on Taiwan's successful experiences, which combined waste recycling and digital solutions to recycle 65% of its MSW (Fig. 1). Although 75% of the MSW generated in St. Petersburg may be potentially recycled into marketable products, waste recovery rate in the city is non-existent. To the best of our knowledge, so far none has reported how the city can strengthen its waste recycling industry through technology transfer from Taiwan in terms of waste recycling using digitalization (Zhao et al., 2020).

With respect to its novelty, this article critically evaluates and analyzes the existing situation of waste management in St. Petersburg and its roles in promoting digitalization-based CE through waste recycling. The challenges in waste recycling that prevent the city from reforming its MSW management are identified. Challenges and lessons learned from Taiwan's prowess in resources recovery are highlighted to inspire a transformation of the city's waste sector towards digitalization. The implications of digitalization on waste recycling industry are elaborated through the lens of social entrepreneurship.

It is anticipated that the Taiwan's mature experiences in digitalizing waste recycling would enable St. Petersburg to play its part to secure a sustainable future. By transforming its waste sector into automation that accelerates a sustainability transition towards a zero-waste future (Figure S1), St. Petersburg could promote its urban development in the long-term without trading offs between other SDGs such as economic growth and poverty eradication. It is the time for St. Petersburg to turn the pandemic into opportunities for entrepreneurship through digital technologies (Verzilin et al., 2019).

2. State of scientific focus and debates on the subject

2.1. Attaining carbon neutrality through waste sector

The United Nations (UN) estimates that about two-third of the world's population will live in urban cities by 2050. As urbanization is the epicentre for social, economic, and industrial activities, the urban landscapes contribute 80% of the world's gross domestic product (GDP). With this demographic dividend, policymakers and business community promote international cooperation to establish it on the global economic

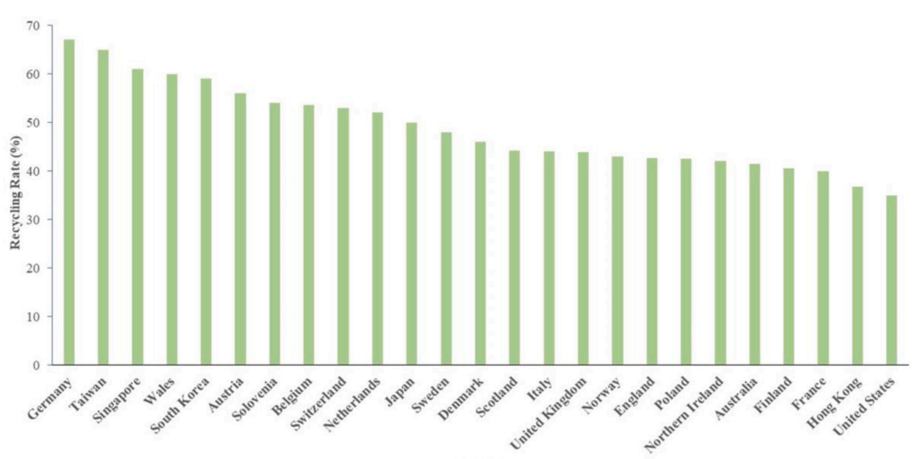

Fig. 1. Recycling rate in developed countries in 2021.

pedestal (Shahbaz et al., 2013). However, an economic expansion without social inclusion may lead to major fall out due to skewed growth and environmental challenges.

As waste generation rates are rising worldwide, solid waste management has become a cross-cutting global issue, which bring impacts on society and the economy. While people move in droves to urban areas, piling garbage also affects cities around the world. Currently cities produce approximately 2.01 billion metric tons (Mt) of solid waste annually (Figure S2) (Kaza et al., 2018), which contribute about 5% of all global greenhouse gas (GHG) emissions, while one-third of the waste is not disposed of in open dumps. Their economic development is further expected to stretch the urban boundaries and population numbers, which would eventually increase the volume of the waste to 2.59 billion Mt by 2030 or 3.4 billion Mt by 2050 with most of the waste originating from South Asia (Pardini et al., 2020). Disposal and treatment of waste result in GHG emission and eventually, leading to their perennial problems. The magnitude of urban development and lack of integrated urban infrastructure also lead to an increasing demand for access to urban services and pressure the delivery of waste collection services in urban cities.

In 2020, waste emission from landfill contributed 5% of the 35.8 billion Mt of $CO_{2\text{-eq}}$ emission to urban cities (Valenzuela-Levi, 2019). With the world's population growth being projected to double in 2050, the $CO_{2\text{-eq}}$ emissions would reach 2.6 billion Mt (Wang et al., 2021), unless the LFG in local landfills is converted to electricity (Xue et al., 2021). Current energy system contributes to about two thirds of global GHG emission. This requires an efficient energy management to achieve carbon neutrality goal (net-zero anthropogenic CO_2 emissions). Achieving the target by 2050 is critical to limit global warming to 1.5 °C above pre-industrial levels according to the Intergovernmental Panel on Climate Change (IPCC). As many as 120 countries contribute to more than half of the global CO_2 emission in total (Hoang et al., 2022).

Carbon neutrality requires profound systemic reform for society and the economy and will have a far-reaching impact on people's wellbeing and the environment. For example, the GHG emissions, attributed to waste disposal in open dumps without a gas recovery system, results in air pollution and global warming, reducing the quality of people's life, and rising socio-economic inequalities among the cities. Increasing resource efficiency, reducing environmental impact, strengthening disaster resilience, and decarbonizing society are also current challenges in the waste sector. Therefore, proper management of urban development is essential to ensure the quality of their life, while promoting environmental sustainability in the long-term (Yang et al., 2020).

2.2. Transformation of waste industry through circular economy

Climate change is a critical global issue that affects both the societies and industries, as the 2021 UN Climate Change Conference in Glasgow has reaffirmed. It is crucial to take concrete steps toward a carbon neutrality by implementing solutions that promote sustainability and economic development. As one of the solutions, greening the sector requires a transformation of waste disposal from landfilling to waste recycling to deal with the MSW. For this purpose, waste segregation for recycling is the first step towards a CE. Recycling refers to "any recovery operation by which waste materials are reprocessed into products or materials for other purposes." (Kurniawan et al., 2021a). Although it is not a single solution to tackle a linear economic model, recycling represents an approach to minimize waste by preserving natural resources and re-using recyclable materials, saving the cost of waste treatment service.

As waste management is everyone's business, moving away from a linear economy model of "take-make-dispose" to a CE is necessary for cities to achieve the 11th SDG 'Sustainable cities and communities' and the 12th SDG "Responsible consumption and production" (Figure S3). The pursuit of both the SDGs requires another global effort, as they may have conflicts with carbon neutrality target. The CE, designed to create a self-reinforcing regenerative cycle, aims at maintaining the utility and value of products and conserving natural capital through continuous cycles, while the linear system results in negative externalities that need to be mitigated (Nguyen et al., 2020).

By adopting CE as its economic model, the European Union (EU) can generate a net benefit of USD 2.14 trillion by 2030, or 50% more than of the linear model. By 2050, the European GDP could increase by 27% by 2050, compared to 15% of its linear economy (Grigoreva and Oleinik, 2016). If properly practiced, the application of CE could maintain secondary resources in production circuit and preserve primary reserves.

2.3. Taiwan's experiences in digitalization-based circular economy

In addition to the EU, Taiwan has promoted CE for its non-biodegradable waste. Its scarcity of resource and raw materials has contributed to its CE-based electronic industry, which serves as a key link of global supply chain. As the Silicon Valley of Asia, Taiwan's experience in resource recycling demonstrates that the most acceptable option for solving the waste problem is through CE via recycling and reuse of wasted materials, instead of conventional end-of-pipe treatments such as landfill and incineration (Wu et al., 2021).

The Island has implemented digital technologies in its waste recycling such as AI image classification for illegal littering using smart containers and GIS systems in a truck route planning for waste collection (Figure S4). Through the Internet of Things (IoT), devices across the value chain are interconnected and communicate with each other over the Internet. The IoT facilitates cities to integrate and share a common communication medium by deploying various RFID sensors. They promote a transition towards a CE-based waste management by collecting data from the sensors such as smart meters in real-time (Vogt et al., 2015).

With an annual waste management per capita of US$ 25.40, Taiwan could be a potential partner for St. Petersburg's entrepreneurs, who have increasingly searched for market access to recycling technology and global market to scale up their ventures (Tsai et al., 2021). Due to its advantages such as free flow of capital and information, technological players in Taiwan are well placed to capitalize on flourishing entrepreneurship in St. Petersburg. Taiwan has the capacity to assist their start-up to obtain exposure to waste recycling technology that meet international standards (Chusov et al., 2018).

As waste recycling gradually becomes a priority in St. Petersburg to reduce MSW, a strong market demand for cost-effective mechanical recycling technologies is anticipated to serve its residents. Although digitalization can promote the development of waste recycling industry, its presence alone is insufficient to create a functioning waste recycling industry (Figure S5). The city still needs appropriate policies to promote technology transfer based on Taiwan's experiences in resource recovery. Hence, drawing lessons from the Island's expertise as one of the world's leading recyclers is essential for St. Petersburg to respond to its urban challenges by using scarce resources appropriately and applying technologies such as RFID sensors and cloud-based software services (Okorie et al., 2018).

3. Methodology

This study investigated how an integrated waste recycling with digitalization that controls MSW generation in Taiwan could be directly transferable and applicable in St. Petersburg to replicate its model of development. Despite both Taiwanese and Russians had varying socio-economic levels, the lessons of MSW management in Taiwan (RO China) might be directly transferable to St. Petersburg (Russia) in terms of best waste management practice in smart cities.

Case-study was selected in this study since it provided a means to investigate a complex waste problem in both cities within their comparative context (Ragin and Becker, 2020). This method facilitated the authors to obtain information that would not be obtained using other methodologies. The data obtained from this work were also of greater depth than that collected using other research designs.

3.1. Study areas

3.1.1. St. Petersburg (Russia)

Geographically, St. Petersburg is situated between 59°93′ North latitude and 30°36′ East longitude in the northwest of Russia in the Neva River delta and on the eastern coast of the Finland Gulf (Figure S6). The country's second largest city has a border with Nuijamaa, a crossing-point in Finland. With an area of 1439 km^2 and a total population of about 6 million people, St. Petersburg has a population density of 3330 people per km^2 in 2020, making it the third most populous city (after Moscow and London) (Chusov et al., 2018). The gross domestic product (GRP) of St. Petersburg grew to Russian Rubble 4.2 trillion in 2018 (US$ 0.06 trillion), while its GDP was RUB 1 million (US$ 13,600) per capita (Fedorov & Kuznetsova, 2020).

3.1.2. Taiwan (RO China)

Situated off the Cross-Strait, the body of water that separates the Island of Taiwan and the Mainland China is geographically located in 23° 70′ North latitude and 120° 96′ East longitude (Figure S7). With an area of 36,197 km^2 and a population of 23.5 million, Taiwan is a densely populated island with 650 persons per km^2, ranking the world's second in terms of population density. The island consists of six special municipalities and counties such as Changhua, Chiayi, Hsinchu, Hualien, Kinmen, Lienchiang, Miaoli, Nantou, Penghu, Pingtung, Taitung, Yiland, and Yunlin (Figure S7). Each county has developed an advanced infrastructure for its waste management from collection, transportation, and recycling to disposal.

For this reason, Taiwan was used as a model of smart city that applied a CE paradigm to optimize the consumption of scarce raw materials and conserve resources. The Island is a miniature of RO China with a sustainable waste management. As there are similarities between Taiwan and St. Petersburg in terms of economic development and industrialization, the former's experience in MSWM might inspire the later in urban development (Fig. 2). As the second largest city in Russia, St. Petersburg was selected to represent the country due to its excessive waste generation recently (Fig. 3).

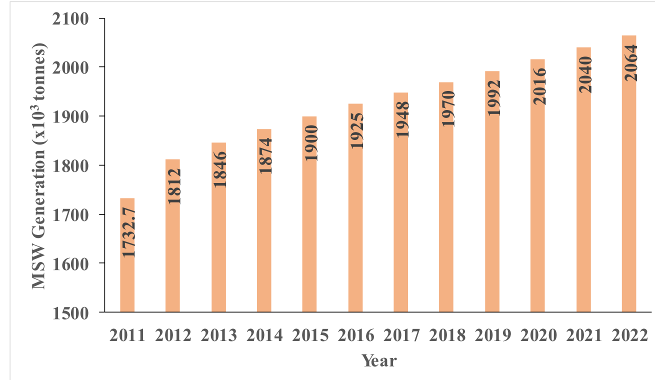

Fig. 3. MSW generation in St. Petersburg (Russia) (2011–2021).

3.2. Data acquisition

To implement this study, the data were collected from primary and secondary sources. Initially, a literature survey was carried out to analyse written documents on Taiwan and Russian environmental policies with respect to MSW management such as the '1987 Waste Disposal Act', 'Digital Economy of the Russian Federation' and Federal Law no.89-fz/1998 on waste production and consumption (Table 1). The secondary data on their respective statistics on MSW were also referred.

A systematic bibliometric analysis was also conducted to understand the emerging research trends and forthcoming research outlook of digitalization-based CE based on the literature available in the Web of Science (WoS) database. This analysis aimed at identifying critical points in the field of digitalization in waste management in Taiwan (RO China) and St. Petersburg (Russia). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guided the article selection (Page et al., 2021). The database search was conducted on April 12, 2022 about the two cities. The search query included TITLE-ABS-KEY (("resource recovery" OR "waste recycling") AND ("digitalization" OR "digital" OR "technology") AND "circular economy").

Figure S8 illustrates the search procedure followed by the PRISMA protocol. As many as 190 records were identified from the database, while 50 records were removed as ineligible (exclusion criteria 1, 2, 3 in

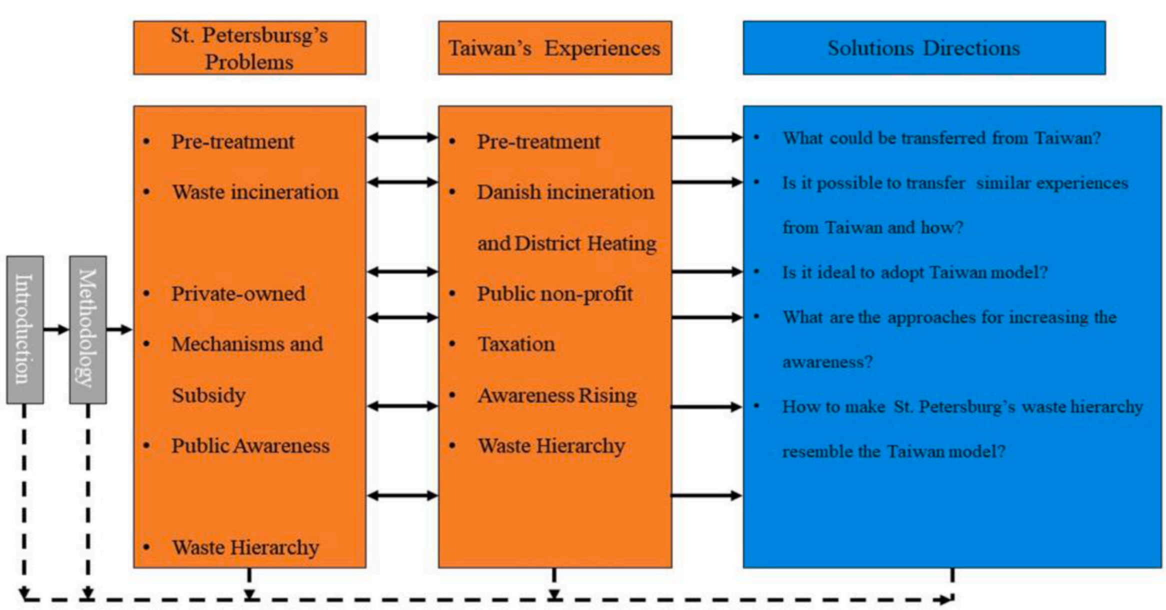

Fig. 2. Conceptual framework of Taiwan's transfer of experience in MSWM to St. Petersburg.

Table 1
Comparison of recycling system in Berlin (Germany), St. Petersbug (Russia), and Taiwan (RO China).

	Germany	Taiwan	St. Petersburg
Recycling laws	Recycle and Waste material Control Act	Waste Disposal Act	Federal Law no.89-fz/1998
Recyclable items	Metals, plastics, paper, and glass	Containers, batteries, motorcycles/automobiles, batteries, tires, lubricants, electrical appliances, computer products, etc.	Metals, plastics, paper, glass, and batteries
Organizational Structure	The private business operates on a volunteer basis; Manufacturers	Recycling Fund Management Board	The private business operates on a volunteer basis; Manufacturers
Participation	Volunteer	Drafted mandatory	Households and volun-teer
Implementation	Green Dot organization and unorganised waste pickers	Government waste collection crews, communities, schools, and recycling industry	"Separate collection" by organization, community, and schools
Payment methods	Pay the Green Dot fee	Pay to the management board, according to EPA-designated rates	Not applicable
Subsidy methods	DSD pays to recycling contractors	Management board pays it, according to the designated rates	Not applicable

Table S1) by the search filters before the screening. The search filter query was: LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"). As many as 140 records' abstracts and titles were screened, while 20 records were excluded according to the inclusion and exclusion criteria 1 to 4 (Table S1). A selected record of 125 articles were sought for retrieval, but 7 records were not accessible. Therefore, 115 records were downloaded for the screening according to the inclusion and exclusion criteria 4 (Table S1). The authors conducted the full-text screening and 3 records were excluded. Finally, this study included 115 articles for further analysis using *NVivo 12.0* software.

The primary data were collected from our semi-structured interviews with city officials, landfill operators, and community leaders (Table S2). This approach was effective in understanding what took place by asking critical questions and evaluating different dimensions of MSW management in the two cities. Respondents were asked about their awareness of digitalization, their interactions with waste management operators, and the level of their satisfaction with waste collection services. We observed those operations available in each city and compared how respondents in different cities reflected to similar questions. As the data used in this research were mostly qualitative, they should be perceived in normative manners.

3.3. Data analysis

As one of the contributing factors to the 2030 UN SDGs, CE has gained popularity among policymakers and private sectors in recent years. The search for novel applications of digitalization-based CE has intensified over the past years, making it influential in the body of literature. Due to its consistent and standardized records in citation analysis, *the Web of Science* (WoS) database was selected to trace and understand systematically among the journals recognized worldwide on how the applications of digital solutions in CE has transformed the waste sector to contribute to the UN SDGS. Relevant articles were chosen based on the keywords "digitalization", "circular economy" with the conjunction of "smart city".

An increasing interest to the CE paradigm has been indicated in its application in the waste sector for resource recovery in recent years. This is reflected by the rising number of CE and/or digitalization-related publications in the body of knowledge between 1980 and 2021 (Fig. 4). The cumulative number of waste recycling-related publications in the same database (1980–2021) significantly soar to 12,441 articles that met the selection criteria. This reveals seminal approaches in tackling the waste problems, particularly non-biodegradable waste (Fu et al., 2017).

4. Results and discussion

4.1. Current waste management in St. Petersburg (Russia)

Recently, St. Petersburg has witnessed an expanding urbanization, characterized by large amounts of MSW generation. As the second largest city in Russia after Moscow, currently the city generates about 11 million Mt of solid waste (Vasileva, 2020). Out of it, 18% (1.97 million Mt) represents municipal solid waste (MSW) (Fig. 5), while only 5% is recycled. The recyclable waste includes metals, plastics, paper, and glass (Fig. 1). The remaining volume is disposed of in 21 landfills widespread in the Leningrad region (Figure S9). As a result, the portion of recyclable waste is small. Consequently, improper waste disposal contaminates the environment, harms public health, contributes to climate change, and hinders economic development in St. Petersburg in the long-term (Rodionov and Nakata, 2011).

Although low-cost biological waste treatment plants represent a promising opportunity to integrate waste sectors in a circular bioeconomy framework, a sustainable MSW management is still not a priority in the city, as reflected by the low investments in the waste sectors by government and the underdeveloped infrastructure of waste management (Abdel-Shafy and Mansour, 2018). As a result, not many bio-products, which resulted from the valorization of organic waste streams, are generated (Atabani et al., 2022). Consequently, the city is overburdened due to a lack of incentives to minimize, reuse, and recycle its waste.

No incentives are available to encourage waste segregation. Its waste collection system is underfunded, while streamlining the waste sector is difficult because the responsibility for waste management in the city is fragmented over various government agencies (Rodionov and Nakata, 2011). Hence, there is a lack of institutional coordination among them. In a world of interdependence, the lack of proper waste management in the city can gradually become a public health problem that facilitates pathogen transfer to the inhabitants. As a result, poor people become the most vulnerable group during a contagious disease outbreak recently.

The current waste management system still follows an outdated model that does not meets the needs of St. Petersburg. With respect to its disadvantages, it is inefficient and practiced through large fleets of trucks that travel daily long distances, in the Leningrad region by unnecessary routes. This adds additional operational costs, waste of time, and environmental damage due to gaseous emission from the burning of fossil fuel, which contributes to climate change problems (Kurniawan et al., 2021a). Other challenges within waste management in St. Petersburg are improper treatment and storage of waste. The lack of a suitable waste utilization in the city leads to a huge loss of useful materials and emissions of hazardous pollutants, which possessed serious effects on the environment and public health (Kurniawan et al., 2021b).

To address the issues effectively without jeopardizing their wellbeing, the city builds a sustainable society through legislations. So far, complexities and variations in waste-related infrastructure have contributed to the current situation. Over the past 22 years, the Federal Law No. 89-FZ on Production and Consumption Waste has been put in

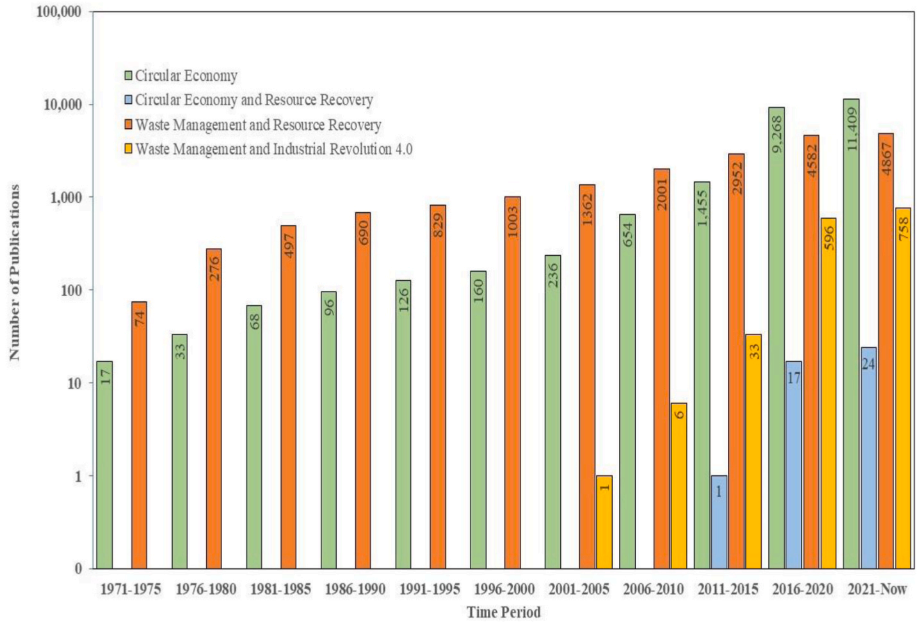

Fig. 4. Publications trends on circular economy in waste management between 1980 and 2021.

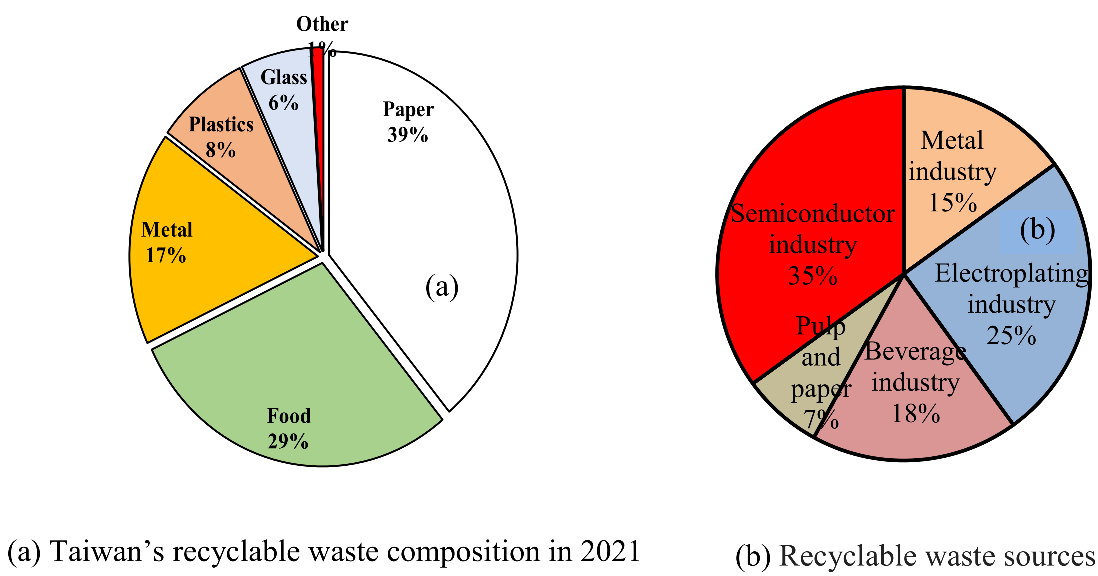

Fig. 5. (a) Taiwan's recyclable waste composition in 2021
(b) Recyclable waste sources
Source: (TEPA, 2022)

force. As the process of collecting and deploying MSW was insufficiently organized, in 2017 the city adopted legal approaches to resolve the situation.

Since St. Petersburg is assembled from complex infrastructures, the key challenges are to integrate different services and harmonize actions to achieve an efficiency of specific urban services. The city has been making an effort to reform its waste management to achieve the UN SDGs throughout the years. However, the Covid-19 global pandemic in St. Petersburg has disrupted the waste collection and treatment systems, representing another challenge to its municipal solid waste management (MSWM) (Figure S10).

It goes without saying that the pandemic is an alarm bell about the consequences of global climate change (Hoang et al., 2021a). It is a game changer that transforms the world, as we know it. A transition to a CE is more urgent than ever. As the Covid-19 pandemic bring impacts on the MSW management, the world gradually shifts from a linear economy to a CE (Hoang et al., 2021b). Although integrating digital solutions into CE is a sagacious strategy towards a sustainable development, opportunities and challenges remain if policymakers do not seriously consider their implications for relevant stakeholders (Hoang et al., 2021c).

Due to the pandemic, the shift in the city's waste management system results in gaps with respect to quality, equity, and efficiency of waste management. This deficient and inefficient treatment of MSW can spiral into a public health crisis if not properly anticipated by its policymakers. Not only the composition of waste collection has changed during the pandemic, but the streams of economic engagement has also blemished amid the lockdown (Kurniawan et al., 2021c).

For instance, the pandemic also appended the MSW streams with new forms of waste such as medical masks. It is estimated that about six millions of medical masks are disposed of monthly, resulting in 19,000

Mt of additional waste (Malchenko and Smirnova, 2019). Although this trash is processed differently as medical waste, it still poses public health risks. If inappropriately disposed of, St. Petersburg needs a decade for its economic recovery, which can derail the city's progress in meeting the 2030 UN SDGs targets. Therefore, the Covid-19 pandemic has turned into a double-edge sword with unprecedented consequences in terms of speed and scale on socio-economic and environmental aspects (Wang et al., 2018). The pandemic has highlighted the urgent need to develop digital capacities that can build more resilient systems in St. Petersburg (Kurniawan et al., 2021d).

An effective waste management infrastructure requires substantial capital resources. For instance, the annual cost of waste treatment is estimated at USD 376 billion (Sarc et al., 2019). Further, the cash-strapped municipality experiences budget deficits during the pandemic. The dwindling public investments in the waste sector and the underdeveloped infrastructure of its management indicates that a sustainable MSWM does not seem to be a priority for the city (Kurniawan et al., 2022a). The private investment is pervasive of endowing resources in waste management due to the low returns of investment (Zhang et al., 2019). During the pandemic times, the public-private partnerships (PPP) models also struggled and/or failed to deliver because 75% of their revenue was linked with user charges, leading to low revenue collections.

As the city's MSWM was ineffective due to its 'throw-away culture' and the rise of one-time use packaging, there is a growing need to technological modernization of its waste management system. For this purpose, St. Petersburg needs to reduce waste generation through reuse and recycling of non-biodegradable waste through CE-based digital solutions (Berg et al., 2020).

In spite of defining 'waste', the city's policies did not define what 'resources' are. If something is not a resource, it is a waste. St. Petersburg municipality needs to turn around this paradigm (Table S3). Rather separating products into 'waste' and 'resources', the city needs to separate products into different types of resources. So far, St. Petersburg recycles only 5% of the waste annually, while the rest is disposed of in local landfills (Ferronato and Torretta, 2019).

With recent economic development, the availability of landfill space has become diminished due to the increasing disposal of industrial waste. Disposal is commonly undertaken by putting the waste on uncontrolled dump sites without any pre-treatment. Therefore, most of the landfills have not been operated professionally, inflicting serious damage on the environment and public health (Wilts et al., 2021).

The "command-and-control" approach has so far been effective in reducing the illegal disposal of the waste. However, St. Petersburg focuses on safe waste disposal without encouraging its recycling. Hence, this policy fails to accommodate new technology in waste recycling. This prevents the city from achieving its zero-waste goal. Despite the city does not undertake waste recycling, private entities provide recycling services due to the pandemic. Therefore, efficient waste collection and recycling should be tailor-made for local situation using technology, while considering its safety and environmental aspects (Fujikura, 2011).

The city's population has increased recently and the demand for new products has also expanded, making the raw materials costly and scarce. Due to their soaring prices, new policies are needed to reconsider the business models of local industry. The CE framework (recycling, recovery, regeneration and reuse) enables products recycling as a route for extracting and turning raw material into high-value products (Figure S11) (Gaeta et al., 2021). Eventually, in the long-run, this benefits society by generating economic opportunities, public health, and environmental protection (Wilson et al., 2012).

Recently, St. Petersburg has intensified its search for new recycling technologies to harness valuable resources from its waste. This includes converting landfill gas (LFG) into electricity as an energy resource and composting organic waste as fertilizer (Fu et al., 2021a). Furthermore, Taiwan's technical prowess in digitalization and its records in resource recovery attract the city to reach out for a win-win collaboration (Figure S12). As one of the most developed cities in Russia, St. Petersburg has advantages in the domain of ICT and financial resources. Technological solutions are essential to protect the environment. By integrating digital technologies into its 'smart city' framework and drawing lessons from Taiwan's experiences in waste recycling, the city could improve its waste management infrastructure. While keeping an eye on the post-pandemic future, the city promoted a digitalization-based CE.

4.2. Lessons drawn from Taiwan's sustainability transition in waste sector

Over the past decades, Taiwan had serious urban waste problems, as its landfills were overwhelmed with mountains of trash. The number of unauthorized dumps increased, while the densely populated island was running out of space to dispose of its waste. The situation with MSW management deteriorated, as trash filled the streets, riddled with vermin and mosquitos (Kurniawan et al., 2011). The main reason for this environmental crisis was that only 67% of waste was collected, while the rest was disposed of in open dumps. This means that 33% of the waste was present in the environment through littering and disposed of outside collection system (Lin et al., 2019).

In 1990s, the waste collection rate in Taiwan was low, while waste recycling was not on its national agenda. Although it can decrease the consumption of primary resources, waste recycling requires energy and generates side streams (Passarini et al., 2018). It seems that recycling did not tackle the causes, except the symptoms. Waste reduction was preferable to minimize the consumption of resources and energy to process it (Lu et al., 2006). Therefore, the Island struggled to clean up the waste without recycling it.

Once known as 'Garbage Island' in the 1980s, nowadays people hardly find any trash, while walking through its street. Taiwan's reforms were started in the 1990s when the Taiwan Environmental Protection Agency (TEPA) implemented revolutionary environmental policies, which effectively reduced MSW generation. A series of economic instruments such as "pay-as-you-throw" (PAYT) tax, where its charge depends on the quantity of trash people generate, changed the manner people in dealing with their trash. Over the past 25 years, Taiwan has successfully revolutionized its approach in MSW management to transform itself to be one of the world's role models in waste management (Chao and Liao, 2011).

After reforming its MSW management using digitalization-based CE, Taiwan has successful stories to share with the world on how to reduce and recycle non-biodegradable waste effectively (Lee et al., 2000). Emerging digital technologies such as artificial intelligence (AI) and Internet of Things (IoT) provide an essential enabler of circular business practices in Taiwan to optimize continual flows of energy and materials back into production processes, making inefficiency transparent. The digital technologies play key roles in Taiwan's transition to CE that facilitates sustainable business operations such as efficient waste recycling, data sharing, collaboration, and shared value creation (Yang, 1995).

Industrial AI is also applied to enhance waste recycling performance, reduce energy consumption, optimize manufacturing and operations, mitigate business risks, and create products with cost-efficiency. By integrating it with existing digital technologies, Taiwan has created a revolution in industrial intelligent solutions, as AI technologies are effectively embedded in industrial products or business services to achieve a faster service, less cost, more reliable products, and higher profit. This investment in AI technologies and digital tools can save businesses and protect the environment that lead to millions of NTW in savings.

Digital solutions have altered how to manage waste comprehensively in the framework of CE. Taiwan's experiences show how digitalization-based CE has contributed to the UN's SDG with respect to carbon neutrality. By adopting digital technologies, the waste recycling industry becomes decentralized, allowing small firms to grow. With the widespread of internet, there is a growing need for waste banks to communicate asynchronously for global connection with one another (Nizetic et al., 2020). Due to the disruptive technology, new business models have transformed the industry to be cost-effective and time-efficient.

With digitalization, Taiwan recycled over two-third of its non-biodegradable waste, an increase of 500% as compared to its recycling rate in the 1980s. As one of the world's leaders in waste recycling, Taiwan recycled the waste and convert it into renewable resources (Fig. 1) (Fan et al., 2012). In addition, the Island's daily per capita rate decreased by 96% from 1.14 kg in 1998 to 0.4 kg in 2015 (Chen and Wang, 2017). This was remarkably lower than the global average of 1.2 kg in the same year. With digitalization, Taiwan achieved a higher productivity and increased efficiency in processes, resulting from innovation gains and value growth opportunity. As efficiency improvement is critical to reduce resource consumption, the paradigm of waste management in Taiwan has changed from 'end of-pipe' to 'digitalization-based CE'.

Taiwan also minimized the amount of waste disposal into landfills to less than 2%, while 80% of its industrial waste was recycled. Due to the successful implementation of 'PAYT' policy and the grassroots efforts, the government converted former landfill sites into public parks and community centers (Houng et al., 2013). Taiwan's turnaround from being a 'Garbage Island' status shows that waste recycling is attainable on its journey towards digitalization-based CE that emphasizes 'source reduction' and 'resource recovery'. This is consistent with international best practices of CE in promoting a sustainable use of non-biodegradable waste for manufacturing. The reuse of recovered waste not only closes the loop between production and consumption, but also makes it become a recycling leader for profitable and sustainable industries (Esmaeilian et al., 2018).

Taiwan's transformation into a hub of CE was attributed to some reasons. As the Island has limited natural resources, it needs to import its energy resources and minerals from overseas (Huang, 2013). Therefore, Taiwan has a voracious appetite of raw materials for its industry. As a steady supply of raw material is deemed as a critical security issue, this creates a strong demand for recyclable materials and a system to efficiently collect and sort out them. Hence, waste prevention and re-use have become the highest priority in its waste management. Before reaching its end-of-life phase, a product's material goes to a cycle of recovery, recycle, and reuse (Clark et al., 2016).

In Taiwan, recycling ranks the third in waste hierarchy, while disposal represents the least favorable options of waste management (Figure S13). The Island possesses a sound system for recycling non-biodegradable waste that earns a global recognition. As a home to global enterprises dealing with unused electric and electronic devices, Taiwan gradually shifts from a recycling culture into a CE through digital platforms. The implementation of CE benefits Taiwan's economy that depends on overseas imports. Although importing is costly, applying CE boosts re-use of scarce raw materials to support its global competitiveness and secure raw materials' supply for its local industry. This approach prevents waste generation and enhances resource productivity, enabling it to address the scarcity issues of the raw materials (Kang et al., 2020).

4.3. Taiwan's waste management reform

To attain a zero-waste society, since 1980s, Taiwan has promoted CE by enforcing effective policies, building a state-of-the-art of waste management infrastructure, and training young generations through education (Chen and Houng, 2004). To adopt a zero-waste framework, the first step is to enact various types of legislations on waste management as a guidance for relevant stakeholders involved in waste reduction activities (Li et al., 2018). This approach provides St. Petersburg with strategic approaches to reform its MSW management, starting from legislation.

4.3.1. Waste disposal Act (1974)

Taiwan's prowess in waste reduction and recycling has evolved over the past four decades with different command and control-based collective environmental policies. As the TEPA is responsible for environmental issues in Taiwan, it initially promulgated the Waste Disposal Act (WDA) in July 1974 to promote waste recycling (Suthar et al., 2016). During their implementation, the regulations of the initial WDA were 'end-of-pipe'-oriented and did not govern the entire products' life cycle. Since the efficiency and quality of the recycling depended on the purity and accuracy of the sorted raw materials, the legislation reforms were inevitable. This helped private sectors with a guidance of responsible design and production of their recyclable products, as well as promotion of renewable resources as materials (Tsai et al., 2021).

In 1988, the Legislative Yuan amended the WDA to prioritize waste recycling and its reduction. Taiwan expanded its recycling system to promote the recovery, redesign, and reuse of valuable waste. The extended producer responsibility (EPR) scheme required manufacturers and/or importers to pay a small fee for manufacturing goods into a Recycling Fund to develop a waste management infrastructure for recycling industries (Tan et al., 2014). Following its 1988 Amendment, the WDA demands manufacturers and importers to undertake resource recovery from MSW for recycling and bear its financial responsibility with respect to 'polluter pays' principle. In addition, the Act required upfront payments that facilitate government to subsidize recycling. The fees were collected on various products and their scope was adjusted periodically based on market change and the development of new products (Tsai and Chou, 2004a, 2004b).

The amendment also mandated public to take their recyclable waste to waste-collection crews. The Article 23 stipulated the penalty revision in case of non-compliance and non-segregation at sources. A fine, ranging from USD 43 to 216 (US$1 = NTW $32), can be imposed (Tsai et al., 2007). For an efficient implementation, the waste-collection staffs were also authorized to reject the acceptance of irregularly segregated or mixed waste during its collection. Illegal dumping was also liable to fine and the government rewarded those, who reported illegal dumping with NTW 600–3000 (εuro 18–91). The inspection process was filmed to provide evidences of their non-compliance (Chang et al., 2008).

As the amount of waste continuously increases annually, the Act has been revised several times. Until 1997 Taiwan's waste management concentrated on fighting against illegal waste disposal and promoting a sustainability transition of waste disposal from landfill to incinerators. Due to the last two revisions in 1998 and 2002, liabilities for polluting the environment were clearly defined in the Act. The amendments took place during 1980s–1990s when its economy started flourishing due to rapid industrialization. While the economy prospered, unprecedented levels of environmental pollution occurred. Resource recycling has become an attractive option and a part of environmental and economic policies to attain 'zero waste' goals in recent years. For this reason, Taiwan has implemented waste recycling policy to extract scarce and critical raw materials from households and industrial waste (Sung et al., 2020).

4.3.2. Recycling fund Management (1989)

Based on the CE concepts, resources need to be used in sustainable ways to their fullest potentials, follow their natural life cycles, and produce no waste. However, carbon neutrality is restricted by resources. Therefore, resources need to be used to create economic benefits by implementing recycling and waste minimization. For this reason, in 1989 Taiwan designed and started its "4-in-1 Recycling Program" based on the Germany's Duales System Deutschland (DSD) system (Yang et al., 2020) by involving community residents, municipal garbage collection teams, recycling enterprises and the RFMB. The 4-in-1 Recycling Program provides market incentives by integrating products' charge and subsidy policy (Wang et al., 2022).

According to the 1997 WDA amendment, the polluter-pays model ensured the sharing of recycling responsibility among local enterprises.

The polluters were supposed to pay fees set by the Recycling Fee Review Committee for recycling subsidies under the Resource Recycling Management Fund. The basis used to determine the fees was practical after taking into account externalities and associated environmental cleanup costs. The manufacturers have to pay the difference between the cost of collecting and recycling their products. The revenues were generated by selling any recovered resources. The fee, based on material, volume, weight, and level of recyclability, was used to cover collection and recycling costs and subsidize licensed companies, who complied with the TEPA's environmental and safety standards, in developing a recycling system. Recycling facilities were audited to confirm the actual number of recyclable materials and to ensure that their operations complied with the regulations (Zhang et al., 2019).

A specific Recycling Fund Management Board has been constituted by the TEPA (Fig. 6). This ensured a smooth implementation of economic instruments such as pay-by-bag collection fee system. With respect to its scope, recycling fees paid by the manufacturers/importers are allocated to the recycling management fund (RMF) and fixed according to the estimated cost of waste collection. The fund consists of a fraction of the TEPA's budget and is administered by the RMF Committee (Abdallah et al., 2020).

In 2012, the recycling fund collected NTW 7 billion annually from manufacturers and importers (Chen et al., 2019). Approximately NTW 6 billion dollars were spent annually on subsidies to recycling companies, which paid collectors, who subsequently paid the residents. About 70% of the funds was distributed to trust funds, which were used to cover the collection or treatment fee for regulated items based on certified collected or treated volumes. The rest was allocated for non-operational fund and distributed to non-enterprise revolving funds, dedicated to education, research and development, and certification for municipalities and administration (Kurniawan et al., 2022b). This fund helped develop new recycling processes and financed educational projects. Since 1998, the fund has been used to purchase over 1300 recycling vehicles nationwide and financed 273 storage facilities for municipal collection squads.

Currently, the RMF, administered by the TEPA, requires the manufacturers of products such as cars, motorcycles, computers, and printers to pay recycling fees to government in the form of recycling funds, subsequently used to subsidize collection and recycling. Either manufacturers or importers of goods pay fees to financial institutions for replenishing the Recycling Fund. The recycling fees received from the manufacturers are fixed and not depends on the degree of recyclability of products. The Fund is used to subsidize back-end collection and treatment, which gives incentive to private firms (certified collection/treatment enterprises) to be involved in recycling activities. Most of recycling infrastructures are privately-owned that work to contract for local municipality (Danilina et al., 2020).

Companies are involved in handling their own waste or paying a waste fee subsidizing a government-run fund for waste infrastructure. Due to the implementation of the '4-in-1-Program' (Fig. 7), the government could finance new projects and allow companies to create a recycling market that consists of hundred companies. The collection and recycling are funded by government subsidy through the recycling fund and independent from the revenues generated from recycled materials (Drozhzhin et al., 2019).

As retrieving valuable substances requires advanced recycling technology, the recycling fund was used to expand resource recycling. Local communities set up recycling centers to sort out valuable resources at recycling points. The fund also subsidized recycling firms to establish a complete recycling system to recycle resources effectively. The recycling not only diverts certain amount of waste disposal from landfills and decreases the amount of the waste under the Program, but also secures high quality materials from households. Therefore, in 2021 its recycling rate was 65%, making it as one of the world's recycling leaders, in addition to Germany (67%) and Singapore (61%) (Fig. 1). For Taiwan, the waste is only a misplaced resource that fails to be reintroduced into production lines. This CE paradigm could be transferable and applicable for St. Petersburg to make use of recycling fund for a digitalization-based

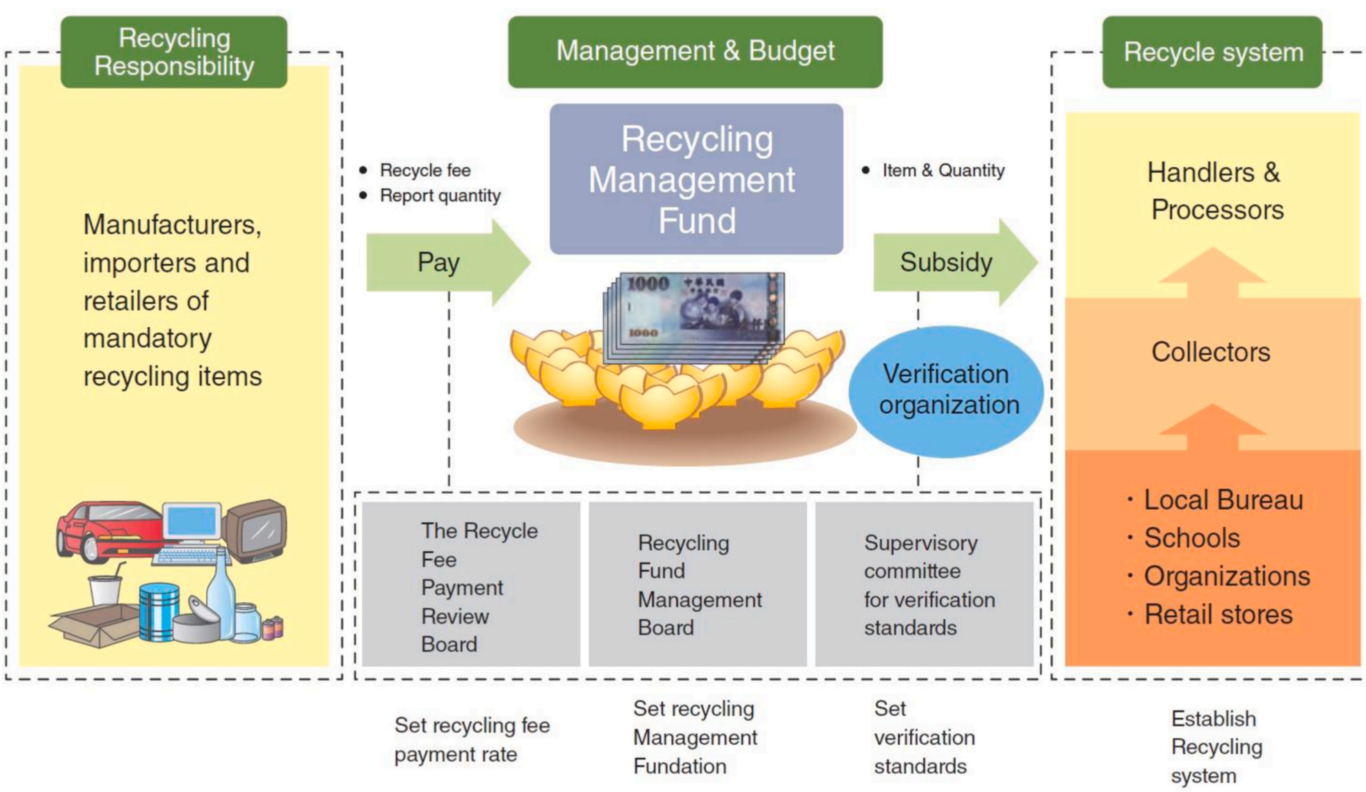

Fig. 6. Operation of resource recycling management fund.

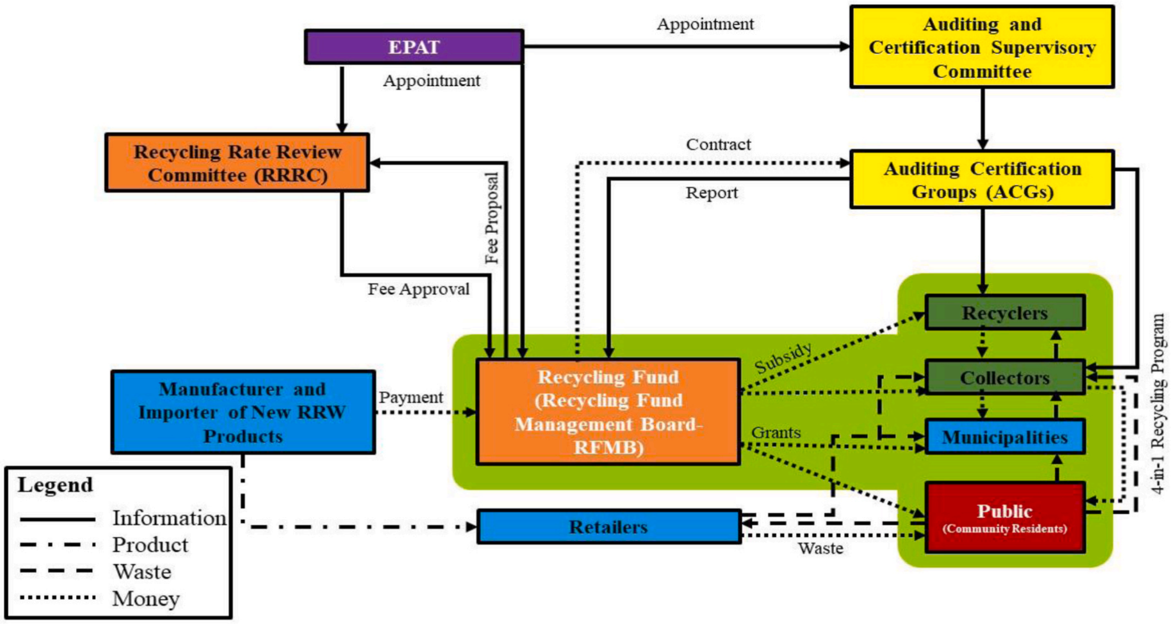

Fig. 7. 4-In-1 recycling program.

CE.

4.3.3. Pay-as-You-Throw (2000)

Prior to July 2000, trash collection and treatment fees were determined based on the volume of water used by a household. In spite of its convenience, as the fee was not directly linked to the actual waste volume, it failed to motivate residents towards waste recycling. Since the fee was not reduced for those who reduced their waste, people could not be benefited directly from reducing the amount of waste they generated (Gong et al., 2020). To eliminate this shortcoming, a volume-based collection fee (VCF) system was introduced since July 2000.

Currently, reduction and recycling initiatives are implemented. The fee, which represents a polluter-pay system, is collected based on 'pay-as-you-throw (PAYT)' according to the volume of trash discarded. To help municipalities in improving waste collection fee, the 'Trash Per Bag Fee Collection' scheme requires residents to pay waste collection fees through the purchase of special trash bags approved by the Government. To enable a significant waste reduction based on the charging of trash collection fees per volume of waste, their price is fixed according to its volume capacity, while their selling and quantity are regulated by the government (Honma and Hu, 2021). The bags have a special logo and vary in color and size due to different districts. The government-certified plastic bags cost NTW1 (USD 0.3) for a small bag, or NTW216 (USD 7) for five large bags. This program helps attain a fair treatment of fee collection and the goals of resource recovery and waste reduction (Moh and Manaf, 2017).

According to the trash volume, the price of the special trash bags covers trash collection and treatment fees. Residents are benefited directly from reducing waste and recycling. Recyclables separated by residents are freely collected by the municipalities. Therefore, people are encouraged to minimize mixed waste generation and promote waste separation (Gupta et al., 2021). The mixed waste must be discarded in these bags only, of which recycling is free and the recyclables can be brought to the collectors. The disposal of mixed waste in Taiwan would cost the resident about NTW 194. If anyone violates this rule, the authority can take his photo and post it online to embarrass those, who do not comply with the regulation. Their photos will be removed after the penalty is paid (Kurniawan et al., 2022c).

The present rate of the fee is US$ 0.013 or NTW 0.45 per L of pay-by-bag (mass-based). Penalties for those, who manufacture pirated trash bags, include prison sentences. This mandatory sorting policy resulted in a substantial reduction in MSW in 2017. About 33% of annual waste generation in Taiwan was reduced due to this "pay-as-you-throw" policy. The average volume of MSW generation per capita decreased by 20% from 1.14 in 1998 to 0.91 kg/day and about 80% was collected by municipalities. In the long-run, this policy mitigates global climate change problems and improves the economy at the same time, as it effectively encourages people to recycle their waste (Hammed and Sridhar, 2017). The same approach is transferable and applicable for St. Petersburg due to its effectiveness in reducing MSW generation.

4.3.4. Producer responsibility Program (2000)

This program, which started in July 2000 under the WDA, required the producers/manufacturers of regulated goods to take responsibility for recovering their spent goods when being discarded by users. Similar to the Germany's Extended Producer Responsibility (EPR), Taiwan's Producer Responsibility Program tackles the issue by requiring manufacturers and importers of products to fund recycling. The manufacturers have to pay for the produced goods and support producers to manufacture products that are recyclable and reusable (Iqbal et al., 2020).

With this paradigm, businesses and institutions collaborate to work on green design and life-cycle analysis to meet the growing demands of environmental protection from global markets. The producers are responsible for changing the design of their products to reduce the waste generated by their packaging. They have to manage their own items after being discarded, taking back materials for reuse or disposal. All stakeholders from manufacturers to consumers are responsible for the waste's lifecycle.

The producers have to dispose of their products and packaging according to the TEPA's recycling standards. Violators will be fined up to NTW 6,000 (USD 184) or publicly shamed. To improve waste reduction rate nationwide, the TEPA expands the scope of the program by developing new recycling technology and strengthening municipalities' recyclable collection (Kurniawan and Oliveira, 2014).

In 2010, Taiwan further enacted legislations that required electronic retailers to take back and recycle their products. The retailers may not charge customers for this service or refuse to recycle. Customers are required to complete forms to ensure the vendors' commitment to recycling and treatment processes. Vendors, who do not meet the regulation, are fined ranging from USD 2,000 to USD 10,000.

4.3.5. Resource recycling and Reuse Act (2002)

Currently Taiwan manages waste and renewable resources based on the two Acts. The WDA strictly treats all disposed materials as waste, while the Resource Recycling and Reuse Act (RRRA) has flexible criteria of recycling and reuse in fluctuation with the market. As a result, the inconsistencies in waste and renewable resource management present obstacles for businesses (Kurniawan et al., 2013). Therefore, the TEPA merged the WDA and the RRRA into one Waste Resource Cycling Promotion Act (WRCPA).

Before the Waste Management Act was revised in 1999, industries had to dispose of their industrial waste on their own. As a result, the waste was abandoned illegally or exported to other developing countries because of incompetent environmental governance, lack of capacity of waste treatment facility, and costly treatment of hazardous waste (Hunsicker et al., 1996). Although the government was not actively involved during this time, the EPA was involved in assisting the operations of private waste clearance companies.

To improve the recycling and reuse of industrial waste, the TEPA further amended the WDA in October 2001 to authorize a responsible government-level agency such as the Ministry of Environmental Affairs (MOEA) for promulgating the reuse of industrial waste and accelerating the formation of "recycle society". The law, "Resource Recycling and Reuse Act'' (RRRA), was enacted and took in effects in July 2002. This Act was designed to conserve natural resources, reduce waste, and promote recycling and reuse of materials from industrial waste sources so that recovered resources could be used sustainably by selling it to contracted companies in a closed loop system. To comply with the legislation, since 2005 the TEPA promoted the "Excessive Packaging Limitation" Policy'. This included mandatory on-line reporting to strengthen the mechanisms of control for the packaging volume ratio of gift boxes (Mao et al., 2021).

4.4. Improvement of waste management in St. Petersburg based on Taiwan's experience in CE

The success story of Taiwan's waste management industry can be traced to the 1998 government fund set up to encourage people for doing recycling their own waste. Though it is not a member of the UN Framework Convention on Climate Change (UNFCCC), the Island's experts are more than willing to share and capable of contributing their expertise to solve this global environmental problem. If its impressive records for waste recycling have been proven recently, the world needs to take into account its advice. Taiwan offers lessons not only how urbanization and wealth can contribute to waste generation, but also how to reduce it at sources systematically and effectively (Table 1) (Premakumara et al., 2014).

To understand how the lessons from Taiwan's experiences have been applied in St. Petersburg, a thorough study of CE implementation by the former is assessed when implementing them. With a recycling rate of 65% in recent years, valuable lessons could be drawn by St. Petersburg from Taiwan's practical experiences in improving its waste management and promoting a waste management culture among inhabitants (Tsai et al., 2021). Once known as "Garbage Island" with serious air pollution, now the Island nation stands as the world's example of what could be attained when undertaking advanced waste management practices. Its inhabitants have increasingly become conscious in their mind and get used to be considerate with their consumption practices. If they generate waste outside home, people have to bring it home with them. Therefore, in public areas, we hardly find any trash. Waste separation is mandatory and becomes a social norm and a civil duty. Such fundamental transformations in culture are necessary for the St. Petersburg to facilitate its sustainability transition towards a zero-waste society and contribute to attaining the 2030 UN SDGs (Bartl, 2014).

For example, Taiwan's 'Keep Trash off the Ground Policy' is transferable to St. Petersburg, except in its remote areas. The waste collection is undertaken by involving frequent fleets at fixed locations. Through a 'door-to-door' system, trucks come to collect waste and residents have to bring their own waste to the trucks by themselves at designated time. Where waste collection is not feasible in remote areas, waste collection service is provided to each household. They have to be present at home at specified time to dispose of their refuse. The 'Trash Does Not Touch The Ground' system makes residents responsible for their waste. Every plastic fork, bottled beverage, and food scrap needs to be accounted by its consumer. This encourages a new relationship between waste generators and their trash (Santti et al., 2020). This policy transformed the traditional waste management system as it encouraged waste sorting at homes by reminding residents to tap for services, and lowering operational costs through an efficient planning and increased coverage (Kurniawan et al., 2022d).

Another lesson from Taiwan's waste management policy that can be emulated by St. Petersburg is to enforce 'reward and punishment' system in its implementation. This encourages people to recycle more and produce less trash. For this purpose, the city needs to mandate a compulsory disposal of non-recyclable trash in certified blue bags. Recycling is free and can be brought to trucks in any kinds of bag. On the other hand, the city needs to have systems in place to punish violators. Video cameras are installed in public areas for surveillance. First-time violators are given a warning, but on their second offense, their video footage is posted publicly. They are also fined up to NTW 200 for committing the violations. Such punishments are used as incentives for the violators in order not to break the rule again (Ferrari et al., 2020).

While public power is important, the CE paradigm in the waste sector has been understood by public, who play key roles in the recovery of waste (Vilve et al., 2010). In Taiwan, waste valorization is not limited to recycling, but to avoiding the production of waste materials. In addition, pubic environmental awareness from industries to consumers are broad. This includes all those involved, who can not demand conscious attitudes from others, who do not follow the laws. Although such an attitude of delinquency is present in all societies, they are avowedly in the minority.

Waste recycling enables people not only to reduce the negative impacts of toxic substances and hazardous waste on public health and the environment, but also turn the trash into cash through social entrepreneurship. By implementing advanced waste management practices, St. Petersburg could develop its waste industry to bring in billions of US dollars from waste recycling. For example, recycling companies specialize in extracting heavy metals such as gold from discarded electronic equipment. If the extraction of such raw materials accounts for 7% of the world's energy consumption, shifting towards reuse of secondary raw materials in electronic goods could help reach the global targets set out in the 2015 Paris Agreement on climate change (Ranta et al., 2021).

To recycle non-biodegradable waste, trash bins may be placed in public places such as convenient stores for particular products (Figure S14). For this reason, the city could establish volunteer groups to help it sort out and recycle plastic waste and electronic appliances. The presence of volunteers may reduce the possibility of improper disposal of recyclables by residents. Plastic bottles are not decomposed, although they are landfilled for a millennium. Therefore, they need to be recycled and reused to minimize their waste (Fedotkina et al., 2019).

To harness new opportunities through social entrepreneurship, applying digitalization from waste collection to recycling could improve the waste recycling industry in St. Petersburg. Based on Taiwan's experiences, moving towards digitalization prevents the disposal of valuable materials into landfills and minimizes the extraction of scarce and raw materials through resource recovery. Nevertheless, what remains unclear is 'under what conditions the growing applications of digital technologies in the waste sector will foster the transition towards a transformation in the Industry 4.0 era' and 'how the pathways of economic circularity develop in waste recycling' (Fu et al., 2021b).

With 65% of recycling rate (Fig. 1), Taiwan can also serve as a role model for other urban cities in Mumbai (India) and Denver (US) (Arya and Kumar, 2020; Badgett and Milbrandt, 2021). The Island took an innovative, green and inclusive approach to waste management, collection and disposal by implementing digitalization. This allows the identification of waste generation points and the management of collection by allocating registered service providers to registered users, ensuring that all collection points are covered as expected. Unregistered residents and other users like industries can request waste collection services through the digital platform, which enables payments to be made for prepaid services and subscription packages, as well as allowing payments back to users. This ensures that government receives its shares of revenues collected (Fu et al., 2021c).

While the two cities still rely on conventional waste recycling in undertaking a CE-based MSWM, Taiwan has empowered digital technology for automation, creation of a waste database, availability of information, supporting decisions on the availability of materials and their applications. This makes its waste sector avoid undesirable sanitary landfills. Taiwan's examples demonstrates that urban waste can go from being a villain to resource when it is properly managed, reducing CO_2 emissions in the long-term and contributing to carbon neutrality (Maiurova et al., 2022).

For this reason, it is necessary for St. Petersburg to develop a long-term waste management plan that incorporates the concept of "polluter pays principle" for financing waste management. The paradigm forces producers and consumers to share the financial burden of recycling and waste collection and gives people incentives to generate less trash and motivate those, who do not have a disciplined habit of waste separation. In addition, economic instruments such as MSW charging scheme need to be introduced to change people's behaviors and raise money for building a recycling infrastructure, waste collection services, and education. Environmental education and community engagement in source separation are essential to represent the Island's prowess in waste management (Russo et al., 2019). In Taiwan, all sectors walk in harmony for promoting transition pathways to carbon neutrality.

The vision of a truly interconnected, borderless world now seems an imminent reality, rather than a distant dream. In the face of the rapid advances, the city's growing reliance on technology has been brought sharply into focus. St. Petersburg has developed a 'Smart City' framework to synchronize waste collection time, pick-up locations, and trucks using RFID sensors to monitor the volume of waste in trash bins. With thousands of potential pick-up spots daily in St. Petersburg, mobile apps helps users track the trucks and alerts them whenever they are nearby. The city uses cloud-based web and mobile applications to track waste as it moves from trash bins to its recycling centers and reuse. The digital solutions can be used to streamline the collection and recycling of non-biodegradable waste. The conventional system of waste collection and recycling relies on informal networks of scavengers, who collected discarded materials manually (Geraskina and Kopyrin, 2021).

This system ensures that relevant stakeholders have to collaborate and are held accountable, while investment in waste collection and recycling facilities (Figure S15), and public participation are the key factors in improving the city's waste management based on Taiwan's experiences. While their conditions vary and unique solutions are still required, the Taiwanese model is an ideal starting point for St. Petersburg to reform its waste management policy and infrastructure (Kamolov and Kandalintseva, 2019).

With thirty years of development, the Island has an advanced waste management, more mature than that of most Asian countries. Its coordinated policies that enforce both manufacturers and consumers to be responsible for what they produce can minimize waste generation and make recycling pay for itself.

Taiwan does not have abundant financial resources when it began reforming its waste management. Nowadays the Island nation has had a multibillion-dollar recycling infrastructure that can handle most of its waste. This implies that developing an effective waste management policy is about willingness (Kunkel and Matthess, 2020). St. Petersburg needs to draw valuable lessons from Taiwan's experiences in dealing with the existing bottlenecks such as immature recycling techniques and underdeveloped solid waste market for recycled products from non-biodegradable trash (Nizetic et al., 2020).

4.5. Perspectives of entrepreneurship in waste recycling industry

To promote the 11th UN SDGs on 'Sustainable cities and community', waste recycling in the framework of CE is essential (Zhu et al., 2020a, 2021). Through waste valorization, waste is converted into useful products, sustainable materials, and other forms of energy. Due to the rapid deterioration of natural resources, providing eco-friendly solutions through waste management has become the need of the hour.

As recycling materials consume less energy than making a new one, waste recycling is important for policymakers to promote sustainable development (Scheinberg et al., 2010). Recycling helps manufacturers minimize GHG emissions by reducing energy consumption. This GHG avoidance results from extracting or mining virgin materials. Manufacturing products from recycled materials requires less energy than making products from virgin materials. If CE practices are enforced, producers have competitive advantages in price competition. Therefore, source separation before waste collection is important to lower its costs and prevent unnecessary losses (Ruohomaa and Ivanova, 2019).

While the Covid-19 pandemic hastens the transformation of waste recycling industries with data analytics and AI, this also shifts business models to a higher degree of digitalization. If properly developed for recycling, the CE implementation for non-biodegradable waste could create jobs (Rajput and Singh, 2020). For example, Taiwan's Da Fon Environment Technology Ltd., a waste reduction and recycling company, focuses on upcycling by turning waste into treasure. Recyclables materials are granulated, washed, and then shipped as raw material to other companies (Tsai et al., 2007). Reintroducing the materials into the supply chain is an important part of the CE. In manufacturing, predictive and preventive maintenance based on machine learning such as neural networks, enables the prediction of failures before they occur, saving repair cost and service time, while extending product' lifecycle. Other industrial AI applications cover forecasting, decision-support systems, optimized solutions, root cause analysis, and data analysis (Fu et al., 2019).

Da Ai Ltd., another recycling company, turns raw materials from recycled plastic bottles to produce shirts, shoes, suitcases, and backpacks. One ton of recycled PET bottles can make about 8000 items of clothing (Owojori et al., 2020). According to the TEPA, one hundred thousand Mt of PET bottles are recycled daily (Tsai et al., 2021) (Figure S16). The bottles, turned into synthetic fibers to make clothing, are collected, treated, and sorted by over 204,000 volunteers (80,000 are regular volunteers, while the rest are part-time volunteers). They sort out the plastic bottles and remove their lids and rings (Figure S17). After transporting them to plastic processing plant to be shredded and washed, the bottles are turned into recycled polyester chips, subsequently transported to spinning mills (Figure S18). At the mills, polyester filaments are extracted and woven into eco-friendly fabrics, which may be manufactured into clothing (Figure S19).

In addition to the clothing, about 63 recycled PET bottles can be made into one blanket (Figure S20). This reduces 1.7 kg of CO_2 emissions, saving 35.4 mL of oil and 6 L of water. On average, Da Ai makes 150,000 blankets daily (Sharma et al., 2020). By using recycled PET bottles as raw materials to manufacture garments, Da Ai promotes a new lifecycle for post-consumer bottles. As long as PET bottles are present in Taiwan's waste streams (Figure S21), the company needs to refine its technology to convert them into clothes. By leveraging its areas of expertise, the company adds value to the unused PET bottles for producing clothes and reduces resource consumption, while conserving energy and lowering CO_2 emissions (Schalkwyk et al., 2018).

To date, Taiwan has over 6,000 registered recycling companies. Reuse of the recovered PET plastic bottles not only closes the loop between production and consumption activities, but also makes the Island become the world's leading recyclers for textiles (Ordieres-Meré et al., 2020). Overall, CE has potential to transform the world towards a zero-waste society. The world is in need of rare materials currently depleting. Waste recycling system can also be improved by applying digital technologies. The use of robotic systems for sorting or cloud computing or IoT for connecting electronic devices and sharing data can enhance waste recycling at the Da Fon Environment Technology and Da Ai.

4.6. Challenges of digitalization and future recommendations

While digitalization transforms waste industry and the economy, the applications of digital technologies may threaten jobs security and raise ethical issues. With the Industry 4.0 paradigms, digitalization's challenges in industry include data, speed, reliability, and interpretability. The bottlenecks of AI's capability in accuracy, validity, complexity, and interpretation of results may affect their performance and reliability of intelligent systems (Kurniawan et al., 2022e).

Rapid digitalization in all its forms would make little sense, unless its bottlenecks are effectively addressed. Relevant investment in digital infrastructure and skills need to have a strong in-built element of targeting certain segments of society in danger of being left behind. This may require elaborate policies that envisage sets of incentives to digital service providers in St. Petersburg (Zhu et al., 2020b).

The digital platforms attract workers regardless of the quality of work available. As workers on digital platforms are considered to be self-employees, they do not have income stability. The lack of income stability and the lack of protections offered by the platforms, and the lack of long-term skills development have left them in precarious situations (Kurniawan et al., 2013). In terms of short-term measures that can have immediate impacts, municipality need to consider how to regulate the digital economy. From a long-term perspective, policymakers have to consider how to make workers get ready so that they can excel in negotiating a decent work (Zhu et al., 2021b). For this reason, policymakers need to find a middle path that enable workers to engage in the economy, while providing them with a safety net protecting them socially without reducing the opportunities created by digital platforms. While an effective implementation is yet to be seen, policymakers need to explore creative ways to provide workers with better rights and protections without impacting the digital platforms (Vidiasova et al., 2019).

While the municipality struggles to create jobs for their working-age populations, such an approach is difficult. Fragmented decisions taken by policymakers reduce the power of government, shifting it to the digital platforms, which can take their businesses to places that are less regulated. Policymakers need to be creative to find solutions that help them to tread a middle path (Li et al., 2018). In terms of a longer-term strategy, they should consider how to reform their waste recycling systems by improving access, creating better pathways to market jobs, and promoting an ecosystem of social intermediaries and private and public partnership to provide skills training aligned with the changing demands of labor market. Multi-stakeholder dialogues that include a variety of perspectives can be a useful approach for designing effective policies (Drozhzhin et al., 2019).

5. Conclusions

Achieving carbon neutrality requires a profound transformation of economic and technological development. As a paradigm for sustainable growth, CE transforms contemporary societies to produce and consume goods towards a regenerative economic cycle, where economic growth is decoupled from resource depletion. However, St. Petersburg encountered a variety of challenges before applying digitalization in waste recycling.

The challenges of MSWM in St. Petersburg included a lack of proper infrastructure in waste management, low public participation and environmental awareness, technological gaps, and insufficient coordination among its institutions. The city needs to draw valuable lessons from Taiwan's experiences in dealing with the existing bottlenecks such as immature recycling techniques and underdeveloped solid waste market for recycled products from non-biodegradable trash. Taiwan's experiences in waste recycling in the era of 4IR has demonstrated the opportunities on how smart digital technologies can contribute to the development of economic circularity and how digital platforms can pave the way for a transition to a sustainable economy. It is obviously clear that the adoption of emerging technologies and associated new business models has a substantial impact on its waste recycling industry by strengthening their roles as a driving forces of CE in promoting sustainable development (Zhu et al., 2022).

This study also has demonstrated that St. Petersburg could accelerate sustainability transition in waste recycling industry towards digitalization by drawing lessons from Taiwan's experiences in resource recovery. Taiwan's 'Keep Trash off the Ground Policy' was directly transferable and applicable to St. Petersburg for transforming the traditional waste management system by encouraging waste sorting at homes and lowering operational costs through an efficient planning and increased coverage. The time has come for St. Petersburg to put itself at the center of a new technological revolution in the Baltic region. The city has a unique competitive advantage, which stems from an undeniably entrepreneurial spirit and an ability to innovate out of necessity.

As the implications of digitalization in waste management, businesses could save material costs by adopting the CE. The consumption of virgin materials could be lowered by 25% in 2030, while a half of GHG emissions could be avoided. The World Economic Forum estimates that the implementation of a CE could potentially add US$ 700 billion in material savings to global economy.

CRediT authorship contribution statement

Tonni Agustiono Kurniawan: project supervision, re-writing original draft; Writing-review and editing, Funding acquisition. **Aleksandra Maiurova:** investigation and data collection. **Marina Kustikova:** project supervision. **Elena Bykovskaia:** data analysis. **Hui Hwang Goh:** resources and project administration. **Mohd Hafiz Dzarfan Othman:** conceptualization and validation.

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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