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Unlocking digital technologies for waste recycling in Industry 4.0 era: A transformation towards a digitalization-based circular economy in Indonesia

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ABSTRACT

The overgeneration of non-biodegradable waste in Indonesia requires empty lands for landfilling, which contravenes with the landscape of sustainable cities. As local landfills have become overburdened, the solid waste is disposed of in uncontrolled manners that seriously affect public health and the environment. To address this problem, Indonesian gradually moves towards digitalization for waste recycling. To reflect its novelty, this work investigates how to add economic value to recycled waste using digital technology and how economic incentives can be promoted to avoid generating waste. The roles and implications of digitalization on resource recovery are elaborated from Cleaner Production perspectives. As a driving force of social innovation, it was found that the digital transformation of waste industry encouraged community in Yogyakarta to sell waste online via *Rapel* app installed in their smartphones. On average, customers sell their waste nearly 15 kg per transaction and earn USD 0.1/kg as a point balance. When their waste ranges from 15 to 20 kg, the sellers get USD 1.4. Recovering polyethylene (PET) bottles via a mixed-recyclables could yield about USD 150–300/Mt, while a bottle-only collection ranges from USD 360 to 590/Mt. As the implications of this study, digitalization has created new jobs (780 waste collectors) in Yogyakarta (@20 persons/subdistrict). Digitalization in waste management also promotes waste avoidance up to 65%. Potential monthly turnover from the waste recycling's transaction through the app is about USD 2,000/waste bank. Overall, the findings imply that the digital transformation in the waste sector not only promotes the resource recovery of non-biodegradable waste for a circular economy, but also enables local community to do online transactions of recycled goods through mobile-based applications. By moving towards digitalization, it is projected that the country's waste recycling industry would create over 120,000 new jobs and absorb about 3.3 million informal workers such as waste collectors.

1. Introduction

In recent years, Cleaner Production (CP) paradigm has become a global benchmark of resource circularity to minimize waste production and GHG emission in manufacturing sector, while maximizing outputs (Fan et al., 2020). Although intensive industrialization has expanded global GDP, waste production is still recognized as a blind spot in manufacturing (Caporaso, 1981). With the increasing scarcity of critical raw materials, a second life of products and used materials becomes an inevitable option to promote a circular economy (CE). Consequently, industrial users gradually shift from a linear economy towards a CE in waste management. This promotes resource recovery through waste recycling and reduces the negative impacts of a linear economy (Fig. S1) (Mohamed, 2010). For this reason, identifying new opportunities and challenges present in recycle, reuse and recovery (3Rs) scheme are important to develop and implement suitable technologies that catalyze innovative digitalization (Turkyilmaz et al., 2019).

In an increasingly complex, interdependent, and interconnected era, digitalization plays critical roles in waste sector to build a global sustainable economy by changing the way companies how to do business, how to organize business, and how to create and capture values (Ayub

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List of abbreviations

4IR	4th Industrial Revolution
5R	recycle, reuse, recovery, reduce, repair
AI	artificial intelligence
App:	application
CAPEX	capital expenditure
CBSWM	community-based solid waste management
CE	circular economy
Covid	certificate of vaccination ID
CP	cleaner production
EU	European Union
GDP	gross domestic product
Gg	Giga grams
GHG	greenhouse gas emissions
ICT	information and communication technology
IoT	Internet of Things
IMF	International Monetary Fund
ISWM	integrated solid waste management
ML	machine learning
MSW	municipal solid waste
MSWM	municipal solid waste management
Mt	metric tonne
OPEX	operating expenditure
PET	polyethylene terephthalate
R&D	research and development
SDG	sustainable development goals
SMEs	small medium enterprises
SWM	solid waste management
UNFCC	United Nations Framework Convention on Climate Change
USA	Unites States of America
USD	Unites States Dollar
WEF	World Economic Forum
WHO	World Health Organization
WiFi	Wireless Fidelity
WoS	Web of Science

et al., 2021). Technological progress allows digitalization to bring practical solutions to waste sector with long-term benefits for society. Digitalization that encompasses CE in the waste recycling has emerged as a growth driver of value creation by enhancing an efficient operation of resource recovery and reducing operational costs with traceability of waste flows (Fig. S2) (Milios, 2021).

In spite of the improvements of MSW management due to integrated solid waste management (ISWM) (Pieroni et al., 2021a), concerted actions on the socio-economic aspects of waste management are required amid the pandemic that has caused detrimental effects on public health. The WHO has declared the outbreak as a global pandemic since March 2020, as the number of victims has rapidly increased across the globe (Singh et al., 2020). The intertwined crises of health and economy in unprecedented geographic and temporal scales prompt cities nationwide to contain their impacts on the society, bringing its economy to a standstill. As a result, Indonesia's economy has been in a rapid downward spiral to recession recently.

Almost two years now into the Covid-19 global pandemic, the world continues to rely heavily on technology for daily life activities and this will not change any time soon. The deadly pandemic has forced people not only to adjust the manner of their living and working, but also to transform waste recycling industry towards digitalization. Recycling business closed, people worked remotely from home, resulting from the impacts of the pandemic on the living global citizenship. To remain competitive in the business during the pandemic time, going digital is an ideal option as it requires no major adjustment in terms of infrastructure (Carter, 2002).

For this reason, returning to the path of economic recovery requires new solutions to the old problem (Veleva and Bodkin, 2018). As conventional methods are no longer effective in promoting sustainable environment, digitalization provides critical solutions by creating new chances to solve existing problems in the waste sector. The improvement of MSWM based on CE paradigm indicates the need of digital transformation to tackle waste problems using a variety of ways at local level to bring cumulative impacts on a global scale. Wang et al. (2018) found that technology gives new impetus to use CE for envisioning a long-term sustainability with customized approaches in a cost-effective manner.

An earlier study conducted by Kurniawan et al. (2021a) reported the reform of MSWM in Yogyakarta (Indonesia) based on community-based solid waste management (CBSWM). In spite of its novelty, their study did not address the digitalization of waste recycling in the framework of CE. Hence, important links in the nexus of economy, environment, society, and technology in the 4IR era were not established in their study. As digitalization issue has not been widely explored, so far little knowledge exists in this area. Therefore, not many stakeholders have been equipped with appropriate knowledge of the field (Balova et al., 2021).

The pandemic not only has added a new dimension of research need to inform, illuminate, navigate, and evaluate the global response to it, but also posed huge challenges for the world in terms of sustainable energy transition by bringing impacts on global energy system (Atabani et al., 2022). To sustain attractive prospects for future energy sector, valorization of organic waste through microbial fuel cells (MFC) has emerged as one of the most promising options to produce bioelectricity in the framework of biocircular economy (Xue et al., 2021; Hoang et al., 2022). While there is a global shift to clean and renewable energy, opportunities and challenges remain if the word does not take into account their policy implications (Hoang et al., 2021a, 2021b).

For this reason, there is a growing need to investigate the intersections of digital technology and the societal dimensions of the waste issues. In spite of the costly waste management (Sarc et al., 2019), non-biodegradable waste is still mixed with other type of waste. Therefore, the current status quo for MSWM using conventional 'end-of-pipe' approach is neither acceptable nor sustainable (Sudibyo et al., 2017). The conceptual framework presented in Fig. S3 indicates the need of a smart solution to the existing waste recycling based on digitalization (Zhu et al., 2021).

The concept behind the platform lies in the fact that low-income populations are sensitive to the price of waste collection at the same time as requiring a better service. Hence, it needs to consider the potential value that waste holds and how it can be harnessed through a simple and user-friendly digital system that not only manages waste collection and disposal, but also leverages income to the community through their participation in waste sorting (Fig. S4). The solution is designed to ensure all income groups involved in the process is benefited somehow.

To reflect its novelty, this work critically investigates how to add economic value to recycled waste using digital technology and how economic incentives could be promoted to avoid generating waste by unlocking a digital transformation of the waste recycling industry in Yogyakarta (Indonesia). This article also explores how Indonesia could harness the benefits of digital transformation to respond to the Covid-19 global pandemic. The roles and implications of digitalization on the resource recovery of non-biodegradable waste are elaborated from the perspectives of CP. An overview about the impacts of digitalization on the waste recycling industry is also provided in the context of sustainability transition.

It is anticipated that this work would make local waste recycling

industries become 'smart' by adopting digital platforms in their business models and increase their resilience during the pandemic by minimizing the risk of health effects on society (Pieroni et al., 2021b). In addition, the outputs of this work would raise public awareness of climate change issues and inspire other cities in the developing world to shift waste management from processing large volumes of non-biodegradable waste towards value creations by producing secondary materials with the right quality for market. Subsequently, this shifts the focus from large volume, low value materials (a market push) to low volume, high value materials (a market pull) (Fig. S5). With an appropriate approach based on digitalization, waste streams can become a source of income for people (Premakumara et al., 2014).

2. Methodology

2.1. Study area

Yogjakarta province with an area of 33 km^2 is located between 7°793′S and 8°12′ South latitude and 110°00′ and 110° 50′ East longitude. It is situated between the southern part of the Central Java province and the Indian Ocean (Fig. S6). With an annual population growth of 1%, the province is home to 0.5 million of inhabitants, accounting for 0.2% of the country's population (Kurniawan et al., 2021c). To limit the scope of the study, Yogyakarta was selected as a study area, as digitalization of waste recycling using *Rapel* app was tested and applied by local community in real settings before and after the pandemic.

The city had a well-structured decentralized system of MSWM, in which the community played key roles in the management of their MSW. In residential areas, MSW collection and recycling were managed by local community at each subdistrict. Households brought their waste to the nearest waste bank unit voluntarily. Afterward, non-segregated waste was sorted out, recycled, and transferred from its source to material recovery facilities, called 'waste banks'. Non-biodegradable waste was separated manually by scavengers at waste banks, which subsequently sold it to small-and-medium enterprises (SMEs) for money.

2.2. Data acquisition

In the beginning, a literature study was undertaken to understand Indonesia's existing environmental legislations on MSWM and its legal policy basis. Secondary information on Yogyakarta's Statistics of MSW was complementary (Iswanto et al., 2018). By applying an empirical approach, primary data were obtained from waste banks through semi-structured interviews with scavengers, government officials, local community leaders, and *Rapel* users (Table S1) (Kurniawan et al., 2021b).

Rapel is an application in the *google* playstore to sell non-biodegradable waste with economic value that has been segregated or sorted according to its categories by the waste owner. Data were collected for the *Rapel* app according to its business model. When users accessed its app, the *Rapel* processed technical data such as internet protocol address, internet device identity (ID) and information about the manufacturer, model, and operating system of the device that they used to access the app. The *Rapel* used the data to transmit the functions of the app, resolved technical difficulties, and provided users with the correct version of the app. The confidentiality of users' data and personal information were protected and secured.

Focus group discussions with waste banks representatives and the *Rapel* users were also undertaken to study if their recycling activity was temporarily suspended due to the pandemic (Iswanto et al., 2018). Data were collected from waste banks to understand typical waste output and its composition as well as community participation in waste recycling activities before and after the implementation of digitalization-based CE. This approach was effective to investigate what happened in local waste industry before and after the pandemic by conveying critical inquiries to the respondents and analyze the events with stakeholders (Fritz and Koch, 2014).

2.3. Data analysis

As one of the contributing factors to the 2030 UN SDGs, MSWM has gained popularity among policy-makers and private sectors in recent years. The search for digital solutions such as AI and ML to the MSW problem has intensified over the past years, making its presence influential in the body of knowledge. Due to its consistent and standardized records in citation analysis, the Thompson Reuter's *Web of Science* (WoS) database was chosen to systematically trace and understand how digitalization in MSWM has transformed the waste sector towards environmental sustainability in the long-term.

After retrieval on March 12, 2022, a literature survey in the *Web of Science* using relevant keywords such as "CE", "digitalization", and/or "Industry 4.0" indicates that recently, the number of publications concerning 'the transformation of waste sector towards digitalization' has substantially increased from 1981 to date. By 2021, over 3,200 'CE', 'resource recovery', 'digitalization', '4th Industrial Revolution', and 'waste management'-related articles have been cumulatively recorded in the database (Fig. S7). This suggests a novel approach in recycling waste using a digital platform (Olivetti and Cullen, 2018).

3. Results and discussion

3.1. Legal framework of MSW management in Indonesia

Linear business model focuses on infinite resources and overlooks their environmental impacts. The model is not relevant with the current situation, characterized with scarce resources and the need to address the impacts of climate change on the environment (Shahbaz et al., 2013). As the earth's resources for raw materials have been depleting rapidly, there is a growing call for a circular production and reuse of materials to address the lack of raw resources in the future. Stakeholders re-think and redesign their manufacturing processes to reduce, reuse and recycle materials, while policymakers formulate legislative frameworks that facilitate a CE and result in safe materials and goods that fulfil societal needs. This promotes a transition from the linear business model to a CE, of which wastes are treated as useful resources (Mutezo and Mulopo, 2021).

For this reason, local waste recycling industry needs to consider material flows, waste production and recycling, the lost in transition, opportunities and barriers for companies such as pro-environmental change process (Menikpura et al., 2013). Hence, it is not possible to change from a linear to a circular economy by passing eco-innovation, unless new legislation provides industries with frameworks other than CP and/or resource recovery paradigms to remain competitive in the business sector. Eco-innovation is the key of future competitiveness, as it leads to less costs, new growth opportunities, and better image of company before its customers (Nizetic et al., 2020).

Like other countries, Indonesia is now moving from a linear economy with foreseeable uses to a CE with unforeseeable uses. Through a CE, the waste is processed back to its source or into other value-added products (Qiao et al., 2020). Therefore, the community's paradigm of waste management started changing. Segregation of waste at sources can increase the amount of waste that can be recycled so that the potential for recycling also grows. This can foster a CE orientation in the waste sector. To change people's behavior, education, assistance and infrastructure provision are needed from stakeholders in waste management (Ferronato and Torretta, 2019).

For this purpose, cities can play pivotal roles in reducing their GHG emissions by scaling-up their modern waste minimization and recycling techniques (Van den Berg, 2016). This requires a cushion of legal status and law enforcement framework with aid from emerging technologies (Pesce et al., 2020). For this reason, a new legal framework for waste management has been enacted as an umbrella of national legislation.

This provides a basis for the country's municipalities to justify their own approach in MSWM nationwide. Each legislation was designed to target certain policy of solid waste management (Table S2).

To align the country's legislations with the 9th UN SDG "Industry, innovation, and infrastructure", policymakers have demonstrated their commitment by ratifying the 1992 UNFCC and the 1997 Kyoto Protocol, respectively, through enacting the Laws No. 6/1994 and 17/2004. Since 2001, the decentralized approach has transformed the way of governance nationwide. The Law No. 23/2014 and No. 38/2007 have directed the regional autonomy and regulations as well as the transfer of autonomy to provincial or city governments. This empowered regional authority to regulate their own areas for the sake of people's interest (Magazzino et al., 2021). Economic decentralization gave local government incentives not only to pursue economic growth targets, but also to mitigate climate change at local level (Schwidrowski, 2006).

In spite of the complexity in local waste management such as lack of waste recycling and insufficient collection services, municipalities have a duty to address the problem creatively (Nizetic et al., 2020). For example, in addressing plastic waste problems, they put forward CE, which aims at maximizing the use of materials in a circular manner to minimize waste production by recovering and reusing as many materials as possible (Pesce et al., 2020). The collected waste is managed and processed by a third party to turn it back into raw materials and other useful products. This pattern of such waste management encourages a transition from a linear economy to a CE (Kunkel and Matthess, 2020).

3.2. MSWM in Yogyakarta based on CBSWM before Covid-19 pandemic (March 2020)

Annually Yogyakarta generates approximately 0.11 million Mt of MSW with its per capita of 0.7 kg/day (Ghosh, 2017). Only 65% of the volume is handled by the city. In 2020, the city spent US$ 105,000 for waste collection and transportation to the local landfills (Putra et al., 2020). Although the municipality spent about 80% of its budget on MSWM, its waste treatment infrastructures have been continuously strained. Unless anticipated, this would bring devastating impacts on public health and the environment in the long-term (Balova et al., 2021).

From a macro perspective, with respect to insufficient collection points and other aspects related to waste recycling infrastructure, local MSWM has encountered several challenges, which requires creative solutions (Sharma et al., 2020). By understanding how to reduce government's expenses on MSWM, digitalization platforms-based reorientation of waste governance system from upstream to downstream may be a plausible solution (Rodi and Wilson, 2017).

Over the past years, the Provincial Environmental Agency and the Regional Development Agency have shared responsibilities for waste management in the city by planning, developing, and implementing coherent policies for technological transformations towards a CE-based waste management. Following collection from households, waste is transferred to a collection center before its disposal in the Piyungan landfill. With an area of 12.5 ha, the landfill, which has been commissioned since 1995, receives about 470 Mt of MSW daily, consisting of 45% non-biodegradable waste (Dhokhikah et al., 2015). Although the landfill was projected to have 25 years of lifespan in lieu of ISWM, it peaked its capacity within 10 years of commissioning (Table S3). Despite spending millions of USDollars for planning, building, and operating the landfill, the projected estimation of its lifespan was not even close. This makes waste treatment infrastructure in the city become strained (Kurniawan and Oliveira, 2014).

As the role of the authority shifts from a controlling function in MSWM to being a stakeholder in CBSWM, concerted actions have been oriented towards reuse and recycling of MSW (Rincón-Moreno et al., 2021). This aids in achieving 30% of reduction in waste disposal and GHG emissions by minimizing the extracting and refining of new resources. With CBSWM, the recyclers at waste banks can earn by selling high-purity recyclables to industry, while the GHGs that would have been emitted from extracting and refining new resources could be minimized (Aljerf, 2018). Although the GHGs are released during transportation, a net environmental benefit could be attained over the consumption of virgin material resources through CE implementation (Fig. S8) (Tapia et al., 2021).

For an effective implementation of CBSWM, the household's role in waste disposal through trash bins of different types (plastic, paper, glass and metal) is critical. So far, metals and glass have been the most recyclable in digitalized forms against the ones that may not have an online market in the first place such as plastics and papers. Since the situation of local markets varies from one city to another, it is not justifiable to conclude that this trend can be converted to a larger scale to cover the entire country.

So far, only 85% of the households separated their garbage at sources before being transferred to waste banks. Although waste segregation at source is the key, not everyone recycles the waste to bring economic and environmental benefits to community (Nizar et al., 2018). They might not understand that economic benefits are experienced by those involved once they start waste recycling practices based on the CE paradigm (Xue et al., 2019).

Customers or SMEs collected non-biodegradable waste from the waste banks. Waste banks are temporary places for handling waste by buying the waste back in terms of a deposit. Local community can deposit their garbage and extract money from the waste bank based on the value of their waste, transforming the trash into cash. On average, each waste bank collects about 150–175 kg of non-biodegradable waste monthly through CBSWM. It employs about 15–18 staffs. Their activities that covered sorting and selling are handled manually. Their presence promotes sustainable waste management by implementing a CE, which aims at maintaining the value of unused materials through 3Rs, thereby minimizing waste disposal into local landfills and avoiding GHG emissions based on the CP paradigm.

Before the Covid-19 pandemic, there were 250 waste banks over 10,000 customers. As independent community, waste banks played roles in waste handling in Yogyakarta because their activities were carried out by members of the community to help people earn money from selling waste and prevent the disposal of valuables in landfills. They also taught people on how to sort out waste, raising public awareness to handle waste accordingly to reduce waste disposal in local landfills. This can be undertaken in residential neighborhoods by empowering local communities. This can be replicated nationwide.

In the framework of CBSWM, recycling activities through waste banks not only provide livelihood for those involved, but also minimize environmental impacts due to the waste (Fig. S9). The waste banks became a tool for stakeholders (government, community, SME, and media) to decrease the amounts of waste to be disposed, reducing the city's operational budget and prolonging the lifetime of the landfills. Currently, there are about 500 waste banks and 3,000 scavengers citywide, who collect, sort out, and sell a huge volume of non-biodegradable waste. Working from morning to evening enable them to earn about US$ 350 monthly on average (Kurniawan et al., 2021b).

Nevertheless, in this informal recycling sector, specific standards in the waste recycling industry are unavailable and the requirements for recyclable materials and recycled products do not exist. As the price of recycled waste is based on a direct agreement between the waste bank and customers, it depends on its conditions and market demand, leading to a tension between waste regulation and market players for material recovery and recycling, as the waste is not properly sorted at sources (Kurniawan et al., 2022b).

As compared to the administrative approach for transforming waste management-related behaviours, the Shanghai Municipality (China) presents an interesting case. Unlike the Shanghai government, which fines individuals or enterprises for illegal activities on waste disposal or to those, who do not sort out their trash according to its type (Kurniawan et al., 2022a), Yogyakarta's government avoids such paternalistic governance practices. However, this does not help enforce public

participation and their environmental awareness. Without an effective governance, MSWM in the city could not achieve its environmental objectives because only MSW with high economic values and conveniently collected is recycled, while the rest is disposed of in landfills (Lawinska et al., 2022). Therefore, the government need to promote recycling of production waste through local legislations. This enables waste recycling industry to thrive for supporting the implementation of the CE in the city (Sanjeevi and Shahabudeen, 2015).

3.3. Roles of CE in strengthening CP paradigm through CBSWM implementation

CE principles reflects CP paradigm. The CE complements and connects CP concepts to make materials and energy circulate for a longer use in each system. This not only contributes to saving virgin materials, but also expands the window of materials circulation and potential recovery. For this purpose, relevant stakeholders in the city cooperate to address the complexity of MSWM by aligning government programs with the UN's 2030 Agenda. Transformation towards a CE through a digital platform contributes to the 12th SDG on reducing waste generation through 'prevention, reduction, recycling, and reuse'. This stimulates economic activities in the areas of remanufacturing and refurbishment. In turn, it will generate new job opportunity. Beyond recovery, a CE assists the waste recycling industry for high-quality secondary raw materials that can be fed into industrial process (Fig. S10) (Boyer et al., 2021). Digitalization enables information flow between the recyclers and manufacturers to produce high-quality materials from residues.

To innovate a new disruptive business model, waste recycling industry needs to adopt a regenerative business model, which considers materials utility through recycling (Korhonen et al., 2018). The ability to recapture used materials after the point of their consumption and return them to a sourcing and production system facilitates the industry to close the loop on supply chains, slows material loop, and narrows the loop with an increased resource efficiency (Taleb and Al Farooque, 2021). Recycling enables the value of products, materials, and resources to be retained for a longer period, while minimizing the waste generation. Therefore, the distinction between raw materials, products, and waste overlaps once a CE is applied throughout the production lines based on the CP paradigm (Fig. S11) (Luttenberger, 2020).

Recycling also enables valuable raw materials to be recovered and reused. If consistently practiced, this maintains secondary resources in the production circuit, while preserving primary reserves. Recycling more materials promotes CE by reducing the consumption of virgin resources in manufacturing processes or increasing recycled materials, slowing down the depletion (Zeng et al., 2017). More recycling results in less waste that ends up in landfills, decreasing GHG emissions (Aljerf, 2016). This minimizes the need to treat the resulting waste and reduces the pressure from extracting virgin resources (Fatimah et al., 2020a).

To reflect the CP paradigm, preventing waste production or decreasing the demand for virgin materials delivers higher environmental benefits than any other options (Patwa et al., 2021). This promotes their recovery and develops a modern waste recycling industry. The policymakers understand that sorting and recycling in waste sector are ingredients to decrease dependence on raw material. Through digitalization, the efficiency of recycling process can be enhanced, while a higher fraction of recycled waste can be improved by sorting (Santti et al., 2020). Modern equipments used for waste collection and treatment contribute to a higher recovery rate because they are properly maintained (Upadhyay et al., 2021).

For this reason, the composition of the waste is important to influence its recovery and disposal. Others include heterogeneity of the waste, uncertainty of its supply, industrial constraints, legal restrictions, and market (Modgil et al., 2021). The economic aspects of the recovered materials benefit recyclers/scavengers, as their economic value can arise from material savings, resale of the waste, its utilization into other materials, benefitting them, and ultimately preventing environmental damage (Santti et al., 2020).

To educate public about environmental awareness on the aspect of 3Rs concepts, a massive campaign could be undertaken in public space or at schools among young generations. For this reason, stakeholders need to be involved in sharing their contribution towards the CE paradigm (Machmud, 2017). Penetration of CE principles into the city's waste sector needs legislative decisions and societal acceptance (Aboelmaged, 2020). The policymakers and local administration play enabling roles in material management by influencing their public in their respective regions (Kurniawan et al., 2021d).

To bring impacts on transparency and good governance, digital transformation revolutionizes waste management industry on recycling materials and its market (Costa et al., 2022). As companies adopt digital tools to create new processes or replace existing ones, they affect other key areas such as working culture and customer experience (Vilve et al., 2010). A digital integration of waste recycling into other supply chains would enable the market to enforce quality standards or the existence of material information from waste sellers. The presence of standards not only ensures a fair practice in the recycling industry and promotes value creation, but also fixes a fair value of recycled goods and strengthens local market mechanisms (Woodard, 2021).

However, standards compliance with recyclable materials in local market only exists for meeting export requirements. In the developed world, the presence of standards for recycled waste and/or recyclable materials is due to the requirement for exports' technological content, as well as GDP and productivity (Hull et al., 2021). With an increasing number of recyclers and used materials being recycled daily, people need to set standards in the waste recycling industry to ensure the quality of recyclable materials, as demanded by the market. The quality of the materials in the city does not meet global standards due to their odor and dirt. What exists in domestic market is not good enough. As a result, local recyclers are dependent on the import of recycled goods from overseas market (Donati et al., 2021).

Unless the city harnesses the benefits of digital transformation for waste recycling, the current approach of MSWM is not robust enough to sustain its economy in the long-term. Hence, the city urgently needs to transform the current material flows of its waste if it is to continue to reap the benefits of waste recycling digitalization (Salmenperä et al., 2021). This requires a commitment from the stakeholders to a sustainable management of waste (Aljerf, 2018). While the Covid-19 pandemic has accelerated a global transition towards a digital economy, the government's roles shift from being a regulator to a facilitator to accelerate it (Davis, 2020) by acting as a catalyst of economic activity in the city. As a facilitator, government can encourage people to use the *Rapel* app for waste recycling. Through a massive public campaign and environmental education, the government can intervene in promoting this digitalization initiative (Esmaeilian et al., 2018).

The waste problem in Indonesia may be solved through collaboration with all stakeholders involved in the waste value chain, starting from upstream to downstream. If there is a massive campaign about the monetary benefits of such an initiative, residents in the range of productive age tend to be willing to participate, depending on the types of available economic incentives. Financial gains, resulting from the waste transaction, may motivate people to use the *Rapel* app. Hence, it is important to create an ecosystem for the waste collection community and waste bank to be integrated with the recyclers. As there are wastes with low value due to limited market and low collectability, industrial players need to develop an appropriate technology for waste recycling (Ethirajan et al., 2021).

Digitalization enables Yogyakarta free from the risk of resource depletion, of which opportunities and challenges for reuse and recycling are preserved without being threatened (Kurdve and Bellgran, 2021). The city cannot rely on its finite resources to fuel its economic growth. The continued depletion of the resources in the city threatens its future. Therefore, economic growth needs to be dissociated from environmental

pressures so that waste treatment technologies will not be impeded and pressed to their limits. This would place burdens on the society.

3.4. Sustainability transition of MSWM in Yogyakarta towards digitalization after the pandemic

Rebuilding global economies in a post-Covid-19 era has never been more urgent than today (Fu et al., 2021a). Countries have to innovate through digital technologies to tackle their physical/social distancing policy so that business activities remain normal amidst the pandemic situation. Digitalization helps improve their governance performance, productivity, cost effectiveness, and competitive advantages. The digitalization not only addresses the impacts of global change caused by the pandemic, but also establishes a post Covid-19 world with characteristics of being more resilient, more sustainable, safer, and more equitable by mitigating the economic shocks triggered by the pandemic. Therefore, leveraging digitalization to mitigate the impacts of the Covid-19 global pandemic on the environment should be a non-negotiable priority in the post-pandemic era.

So far, all countries still have faced economic fallout from the pandemic. The International Monetary Fund (IMF) estimates that the global GDP shrank an unprecedented 3.3% in 2020 — the world's worst recession since the 1929 Great Depression (Zhang and Chen, 2019). Recoveries diverges across and within countries in the Asia-Pacific region, creating a large gap in living standards. The severity, uncertainty, and duration of the pandemic and lingering economic implications shrank Indonesia's economy by 2% in 2021 (Statistics of Indonesia, 2021).

The long-term impacts of Covid-19 pandemic challenges the global society into the coming years. Restricting people's mobility and border lockdowns affect people activities that involve labor participation. They continuously affect the world's socio-economic systems, while environmental degradation does not lessen (Fu et al., 2021b). As there is a window of opportunity to tackle the challenges such as climate change and Covid-19 as an interlinked priority, economic recovery through a sustainable transition towards decarbonization has become the need of the hour. How the world responds to the ongoing pandemic is important to determine its economic prosperity in the long-term (Kurniawan et al., 2022c).

In the era of 4IR, digital technologies enable business to grow with a limited budget and/or resources. Therefore, SMEs can use digital platform to make their online business grow. Current mobility restriction due to the pandemic provides opportunities for entrepreneurs in the waste recycling industry to grow in business creatively by unlocking disruptive digitalization and digital trade services via apps installed in smart phone. Gradually the entrepreneurs can adapt to a variety of digital solutions available in the *google* play store to respond to their customers' needs during border lockdown amidst the country's social distancing policy (Kalar et al., 2021).

Although the adoption of CE-based digitalization is not simple for business ventures, it has immense benefits to socio-economy and the environment (Chauhan et al., 2022). The city's digital transformation requires private sectors to transform themselves. Emerging digital technologies pave the way for SMEs' growth and optimization. Yogyakarta is well-positioned to transform its MSWM by promoting a low carbon transition in the waste sector through mobile applications. For a transition toward sustainable development, it is crucial for the city to identify and define the scope and output of the transformation.

In addition, business needs to drive its operation and performance through digitalization to satisfy customers (Gong et al., 2020). This transformation means incorporating digitalization into all areas of business to change how companies operate and deliver value to them. As a strong driver of change, companies need to adapt their business models to remain competitive in the business (Deng, 2017).

Over the past two years, the Covid-19 pandemic has brought tangible impacts on waste recycling activities (Fig. S12). Economic activities came to a halt as the special province implemented lockdowns to prevent the escalation of the pandemic. Trends of job losses have continuously escalated recently and vulnerable workers like self-employed workers, migrant workers and workers in SMEs are at risk of losing their livelihoods (Kang et al., 2020).

Although over 4,000 SMEs are involved in the city's MSW business, only a few of them harness the benefits of digitalization. Yogyakarta's inhabitants gradually adopt the digital platforms for encashing their recycled waste online, as the web-based landscape supplies market with the material information from the waste sellers. This boosts the overall recycling rate in the city by matching a waste supply with market demand. As waste sellers are responsible for the products and material sold on the platform, the quality standards of recycled goods and/or recyclable materials are taken care through publicly available material information (Burger et al., 2018).

In this emergency situation, local entrepreneurs have encountered rapid transformations and started leveraging new technologies to adjust their business activities in the waste sector (Fig. 1). A proposed solution to this issue takes an inclusive approach by using a digital platform, whereas people can freely sell and buy their own waste using certain apps (Henry et al., 2021). This idea 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. Unregistered residents like hotels can request waste collection services through the platform, which enables payments to be made for paid services as well as allowing payments back to users (Maiurova et al., 2022).

Shortly after the Covid-19 outbreak widespread in the city, in April 2020 Anang Widarso and Berthy Jacob established PT. Wahana Anugerah Energi. The technopreneurs created and promoted *Rapel* app as a solution for sorting, recycling, and selling recyclable and non-biodegradable waste collected from household and industry citywide. The waste was sold to waste collectors, who already became *Rapel*'s partners. Users and collectors got points from waste trading activities, and their points could be exchanged with various prizes. Through this venture, the collection of minor waste can be tracked and documented. By keeping the generated waste within the CE (Fig. 2), after sorting, the waste recirculates in the recycling market until it achieves its end-of-life cycle. The platform, available in the *google* playstore, aspired to be the most complete waste management solution in Indonesia.

Addressing the issue of unmanaged waste is interdependent from the 'waste ecosystem'. As it cannot thrive alone, the *Rapel* works with other business partners to support its activities during this transition (Aljerf and Choukaife, 2016). This represents a multi-pronged long-term collaboration among the stakeholders (waste collectors, processors, and generators) at local level for a resource-efficient, circular and low-carbon future (Veleva and Bodkin, 2018). Building a strong foundation for a CE requires coordinated actions. Shifting to a CE model affects all sectors and policy domains. The CE paradigm can help techno-preneurs to engage and coordinate with waste collectors in MSWM (Cheng, 2017). The informal actors can be business partners in transforming the waste industry from linear economy towards a CE model.

For its daily operation, the company undertakes business partnership with informal actors like local scavengers. As employees, they help the company to collect and sort out non-biodegradable waste from households, restaurants, and hotels in Yogyakarta (Kumar et al., 2021). The waste segregation starts from large non-biodegradable waste materials before it is classified according to its type such as plastic, or metal. To reduce GHG emission and improve their quality, the waste materials undergo testing (for *e*-waste) or treatment before being further processed into recycled secondary goods (Ibrahim et al., 2018).

The current focus of the venture is non-biodegradable waste due to the market demand of high value recycling, transforming it into materials such as metal useful for manufacturing industries (Mohammadi et al., 2021). To support its financial sustainability, the involvement of

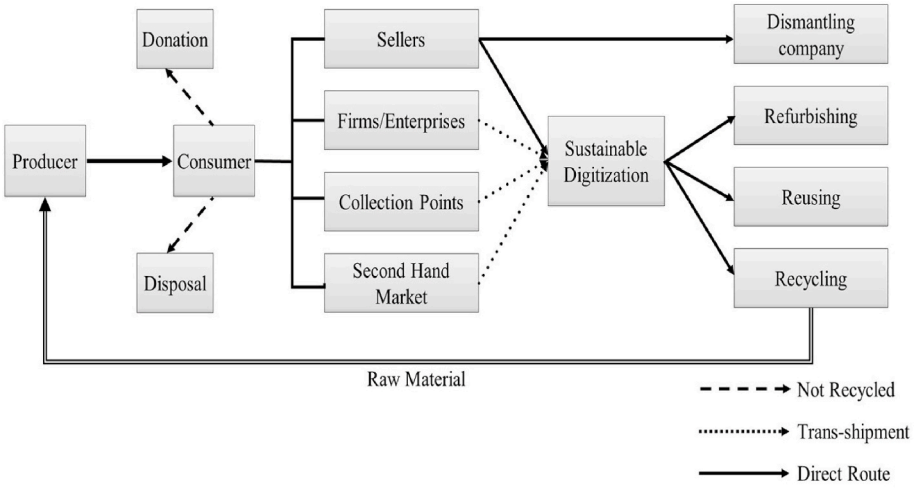

Fig. 1. Sustainable digitalization in waste management industry.

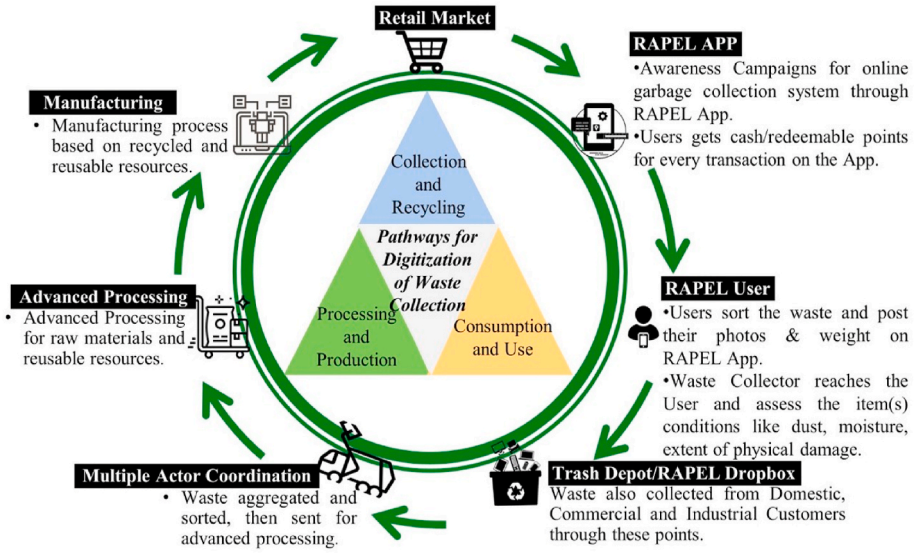

Fig. 2. *Rapel app* contributes to non-biodegradable waste reduction in Yogyakarta.

public health centres, hospitals, and laboratories will be expanded beyond non-biodegradable waste to cover the biomedical waste from them (Augurzky et al., 2012). This would increase the sale of recycled and refurbished items across the value chain and diversify the revenue streams and financing mechanisms (Figge et al., 2021).

The unprecedented socio-economic crisis caused by the pandemic has highlighted the roles of digital finance in providing solutions for waste industries. As digital finance is the key for industries to become more resilient and more sustainable (Islam and Huda, 2019), harnessing digitalization to accelerate the financing of the SDGs could have major impacts on sustainable development. Unleashing digital inclusion in the waste sector enables affordable, effective, and safe financial services for everyone to use mobile money, online accounts, electronic payments that reach those, previously excluded. Hence, digital finance provides financial services efficiently with widespread benefits. Mobile payment technology have transformed mobile phones into financial platforms (Fu et al., 2021c). Local banks in Indonesia invested over US$1 million in developing, integrating and acquiring financial technologies. They deploy new financial arrangements on apps to promote digital inclusion (Nandi et al., 2021). This shift towards social financing creates an opportunity to unlock capital that advances digital inclusion to contribute to the UN's SDGs.

In spite of its benefits, the barriers to realize financial inclusion services include inadequate digital infrastructure, affordability and capability, minority biases, and cyber vulnerability (Hunka et al., 2021). Digitalization also introduces risks such as privacy violations and data security breaches, fraud, irresponsible lending, and discrimination based on profiling. The risks may further divorce finance from people's needs. To mitigate them, technological improvements play roles to develop the quality of digital infrastructure with respect to security and safety of digitalization (Otto and Drechsel, 2018).

Today's digitalization of financing has already delivered financing for SDGs. The DNA of digital finance such as data protection on risks and impacts, cheaper and wider accessibility of financial services, is already harnessed. This demonstrates that digital technologies are unlocking new pathways for rapid economic development, job creation, and access to services in finance, education, and waste management. For digitalization to be a true force for delivering on the SDGs, technological advances in digital platforms need to be combined with a sound policy that empowers citizens to be involved in this journey.

To contribute to the SDGs, the *Rapel* app bridged the technical barrier and create economic opportunities for businesses and netizens by streamlining recycling process. The city's MSWM scenario can be transformed towards a CE by providing knowledge and data for public

consumption with accurate information on the availability, location and condition of the waste and cutting down on conventional recycling stations, where informal entities reclaim precious metals from *e*-waste (Shaikh et al., 2020).

The improper disposal practices of e-waste by scavengers creates unsanitary conditions that lead to occupational hazards and environmental pollution (Zhu et al., 2020a). Coping the technical barriers with the 3Rs concepts improves MSWM (Grafström and Aasma, 2021). Hence, there is a growing need for increasing public awareness and participation towards such practices and elucidating the economic value of the waste through web-applications (Maitre-Ekern, 2021). This can create job opportunities and add new sources of public revenues. The integration of digitization and top-down policy goals such as a 30% of recycling rate for household waste by 2025 creates opportunities for app-driven solutions.

After the pandemic, the current number of the *Rapel* users (waste collectors and waste sellers) in Yogyakarta is about 10,800 people. The digitalization has created new jobs for 780 waste collectors in the city (@20 persons/subdistrict). This suggests that the digitalization of waste industry depends on the engagement and participation of local community as waste collectors.

From the operational points of view, the company provides the waste collectors with uniform, identification cards, and waste handling equipment. This enables the *Rapel* partners to get a hassle-free authorised entry into secure residential housing clusters. This fact suggests that the company's mission, vision, values and goals fit well with external factors such as local environment, culture, and social in enhancing recycling and proper waste management with responsibility for waste workers and society at-large (Zhu et al., 2020b). Through this approach, the *Rapel* can provide the best services and solutions that have added-value in the waste sector for all stakeholders.

The *Rapel* also envisions to build sustainable societies by actively participating in environmental care to improve the quality of life. For this purpose, the internal organization fits well with its missions to contribute to environmental improvement by implementing a CE for providing a sustainable waste management from upstream to downstream (Kasim et al., 2021). Therefore, the *Rapel* encourages all employees and its partners to have a sustainable growth in their lives. With respect to internal fit, the internal components of the company such as manpower complement and reinforce to each other (Chauhan et al., 2021).

With respect to its concept, whenever customers advertise the picture of their sorted waste with attributes like weight (at least one kg) and physical conditions in the *Rapel app*, a waste collector will visit, evaluate and procure after verifying with specifications like dust and dampness of trash. Then, this procured waste is sold to the *Rapel* via waste collectors (Fig. 3). Apart from cash, customers and waste collectors obtain points from their transaction on the platform as *Rapel*'s balance. The points can be exchanged with various gifts based on the *Rapel* points according to available promotion (Fatimah et al., 2020b). The gifts vary from napkin, tissue, washing soap, toothpaste, and children toy.

On average, customers sell their waste nearly 15 kg per transaction. This helps them earn equivalent of USD 0.1/kg as a point balance. When their waste ranges between 15 and 20 kg, the sellers get USD 1.4. For example, recovering the PET bottles' material value via a mixed-recyclables could yield about US$ 150 to 300/Mt. The highest value, which ranges from US$ 360 to 590/Mt, requires a maximum level of aggregation, in the form of a bottle-only collection.

With respect to its volumetric turnover, the company managed 51 Mt of non-biodegradable waste monthly sold by the customers (Fig. 4). This suggests that the *Rapel* app alone contributed to 22% of total waste reduction or 68% of non-biodegradable waste reduction monthly (Fig. 5).The composition of the waste included plastic (20%) and paper (60%), while the rest consisted of metal, glass, and cardboard (Fig. 6) (Mashkoor et al., 2018). The Covid-19 global pandemic changed waste generation and its composition (Naughton,2020). During the pandemic, medical waste generated from healthcare facility increased exponentially nationwide (Mayer and Gottlieb, 2021).

The digitalization of waste management promoted waste avoidance up to 65%. This rate was higher than 30%, the target set by the country's Environmental Ministry. Potential monthly turnover from the waste recycling transaction through the *Rapel* app was about US$ 2,000/waste bank. The digital platform represented a strategy to reduce waste generation and improve local economy. The findings shows that public participation, societal acceptance and their engagement with the digitalization platform are the key solutions to the city's waste problem

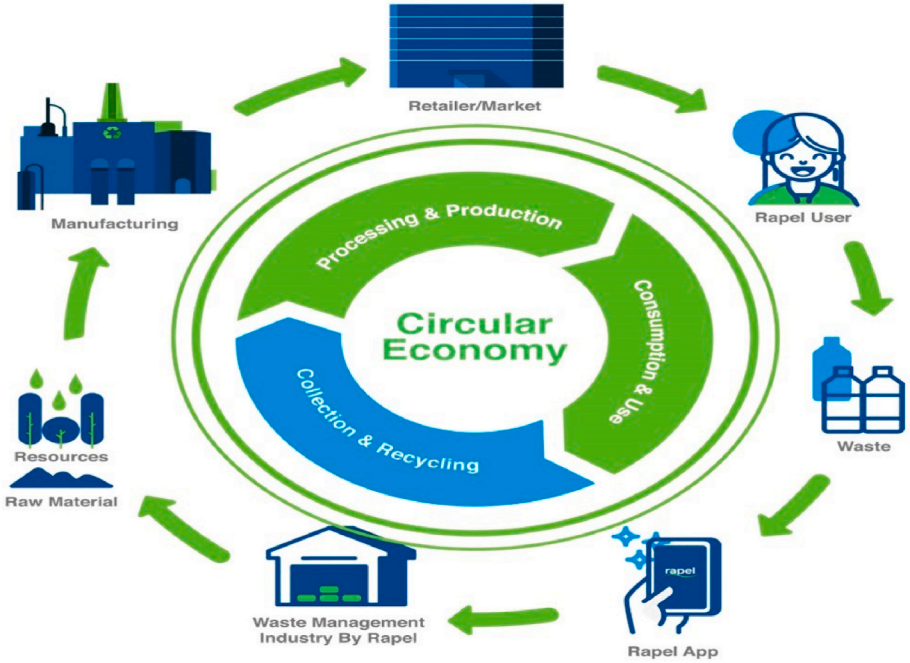

Fig. 3. Working mechanism of *Rapel app* in waste recycling industry.

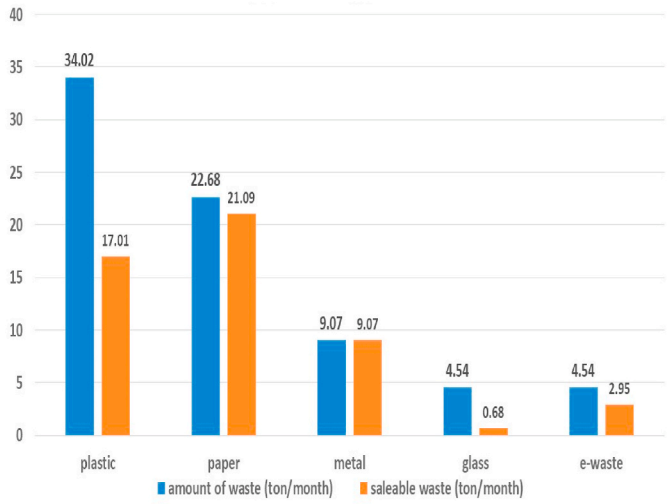

Fig. 4. Estimation of non-biodegradable waste sold through *Rapel* app.

Total of Waste (ton/month)	Non-organic Waste (ton/month)	Sold Waste (ton/month)	% Waste Reduction to Total Waste	% Waste Reduction to Non-organic Waste
226.80	74,84	50,8	22%	68%

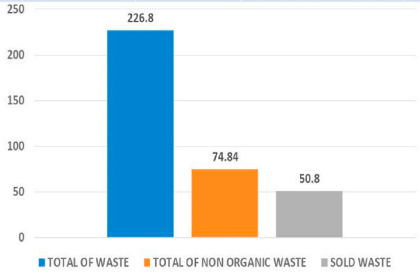

Fig. 5. Estimation of non-biodegradable waste reduction through *Rapel* app.

Fig. 6. Types of trash that can be sold through *Rapel* app.

(Maitre-Ekern, 2021). The flexibility and autonomy of running the *app* make it possible for users to have benefits from the system according to their needs.

As compared to the *Rapel*'s contribution to city's waste reduction, the conventional waste recycling industry by the community based on CBSWM recycled 10.54 Mt of non-biodegradable waste. This contributed 14% to waste reduction (Fig. 7). When the *Rapel* app was combined with conventional recycling waste industry, the Yogyakarta province managed about 147.19 Mt of non-biodegradable waste monthly. This not only contributed to 65% of waste reduction in the city (Fig. 8), but also avoided 0.2 Mt of GHG emissions. With digitalization in waste management, the implementation of CE based on CP paradigm became more effective than that of traditional CBSWM.

Type of Waste	Total of Waste (ton/month)	Total of Recyclable Waste (ton/month)	Reduction Waste Percentage
Organic	113.4	96.39	85%
Non Organic	74.84	10.54	14%

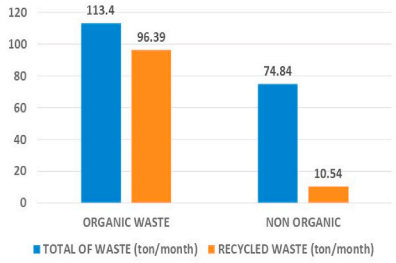

Fig. 7. Waste reduction by recycling industries (community).

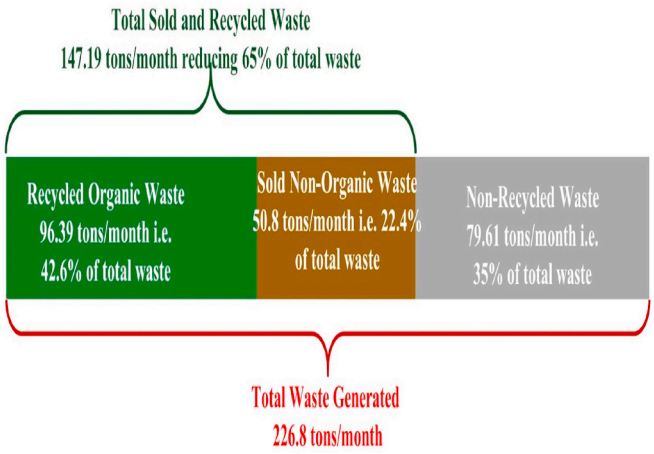

Fig. 8. Estimation of waste reduction from combined *Rapel* apps and local recycling industry.

Although the waste reduction rate does not directly correspond with the reduction of government's total expenses for the city's MSWM, this results imply the need of a mutual cooperation between municipal waste management authorities and private actors. In addition, an adequate legal framework and adherence to the rule of law need to get ready in place to facilitate an eco-friendly waste management citywide (Okorie et al., 2018).

Recently the company has expanded its operation to cities in Central Java Province such as Semarang, Surakarta, and Magelang (Fig. S13). Although it is feasible to undertake logistics of recycling waste across long distance through local couriers, short distance within the same island is preferable to long distance to another island due to the consideration of logistic cost. Due to the logistic issues, excise taxes and custom duty consideration, such an initiative is more cost-effective if it is implemented nationwide, rather than being introduced cross borders (Ordieres-Meré et al., 2020).

The digitalization in waste sector encourages people to separate their waste at sources during the pandemic. With digital apps, the registration, tracking, and reporting process can be accelerated during waste collection due to a barcode reader feature. Using the scan barcode system on a mobile phone, digitalization can help waste collectors quickly identify the waste's types, quantity and its owners without having face-to-face interaction during the large-scale physical/social distancing (Rajput and Singh, 2020).

The digitalization also extends the coverage of waste recycling industry and lowers transaction costs, while increasing information transparency through virtual interaction (Kamble et al., 2021). By

altering the way of man-to-man interactions and lowering the costs, digital economy is not only an economic transformation, but also a revolution of social interactions that changes the manner people live and work. In Indonesia, improving people-to-people connections provides essential conditions to eliminate development gaps and promote inclusive growth through improved connectivity. This provides not only proper infrastructures for connectivity, but also a smooth transfer of information flow in a cyberspace domain (Finch et al., 2021).

To expand its networks in the country's digital landscape, the company had partnership with the *Gojek* to enable users' *Rapel* balance to be redeemed into a *Gopay* balance. As a digital payment gateway, the *Gopay* enabled the payment to waste sellers to be completed directly at the same time on the merchant's website (www.gopay.com). Cloud technology not only helped the SME manage password, customer relationship, and e-mail efficiently, but also improved its operations and productivity by moving to the cloud (Ruohomaa and Ivanova, 2019). Doing so increases their revenue, thereby setting them ahead of the competition. For customers' benefits, the *Rapel* update the unit price of the waste biweekly on the website (www.rapel-id.com). All the information presented on the website can also be accessed via a mobile device (Baars et al., 2021).

3.5. Comparison of Rapel and other waste management apps

During the pandemic, business sector closed and people had to work remotely from home due to the country's large-scale social distancing policy. To survive amidst the worsening circumstances, Indonesia's waste recycling sector went digital. For millenials, if there is no innovation, there is no progress; without progress, their waste business stagnates (Schwanholz and Leipold, 2020). Therefore, many waste management starts-up were established to develop digital apps to deal with the mobility restriction due to the pandemic. For this reason, online business in the waste sector remains attractive and competitive due to the presence of various digital apps (Abdallah et al., 2020).

Although the *Rapel* was the pioneer of waste recycling *apps* in the study area, other apps also exist in other cities in Indonesia. Depending on their residency, people have other options to evaluate and compare the efficiency of *Rapel* to those of others such as ease of its use with respect to their recycling products online (Ferrari et al., 2020).

Apart from the *Rapel*, another waste management app '*Waste4-Change*' provides services in several cities nationwide; the *E-Recycle* in Jakarta; the *Kepul* in North Sumatera's Medan; and the *Octopus* in eastern Indonesia, Bali and West Java province. Like the *Rapel*, the *E-Recycle*, and the *Octopus* apps allow users to exchange recyclable waste for cash or points that can be redeemed as vouchers, or transferred to an *e*-wallet (Alonso-Almeida et al., 2021).

Plasticpay, launched in April 2019, is another app that offers *e*-wallet points for users, who actively collected plastic bottles. The plastic bottles collected by the app users are recycled to make synthetic fibers and pillows with recycling technology. The machines shred the plastic bottles and processed the material into a soft fiber similar to cotton. Unlike the *e-Recycle*, which provides pick-up services, the *Plasticpay* encourages its users to deliver their plastic waste to available drop-boxes due to logistic expenses. The *Plasticpay* also welcomes scavengers to deposit plastic bottles in its drop-boxes in exchange for USD 0.2/kg, a higher rate than that is offered by regular plastic collectors (Kurniawan et al., 2021a).

Various apps accept different types of waste. The *Octopus* only takes plastic bottles made of PET materials, while the *Rapel* accepts plastic, paper, metal, and *e*-waste. The *E-Recycle* sends collected plastic waste to its recycling facilities and processes it into plastic pellets, while the *Octopus* connects its 8,000 waste pickers with 1,600 waste banks and other collection facilities (Iswanto et al., 2018). As the age group of users is important in market segmentation, participation of people older than 30 years old affects the preference in the type of waste management apps involved, recycled waste, as well as the amount of waste recycled (Khan et al., 2022).

3.6. Global transformation of waste sector in 4IR era towards digitalization

Digitalization has gained popularity recently when it becomes one of the government's emergency responses to the Covid-19 pandemic crisis such as the enforcement of physical distancing and border lockdown policy. As a result, society have implemented online working and shopping activities to substitute offline meeting. Without digital platforms as the solutions that connect people and business, the pandemic might have harmed the global economy in the long-term more profoundly than what is anticipated (De Morais et al., 2021).

Embracing digitalization in waste recycling industry provides a strategic move essential to make a leapfrogging progress, as this enables the industry to shift its business model towards sustainable solutions that not only improve cost-effectiveness, but also reduce operational costs. With digital technologies, waste can be tracked and maintained efficiently, which makes it easier to extend their useful lives. By having full knowledge about the nature of the waste and its fate, recyclers not only can identify the used materials from online platforms, but also reduce the demand for virgin material resources (Juware and Mirashi-Shirsath, 2020). Ultimately this reduces GHG and conserves natural resources simultaneously (Chu et al., 2019). The world stands at a historical turning point to balance between economic growth and environmental protection using digitalization (Wijayanti and Suryani, 2015).

To elaborate how digitalization affects economy and society, it is important to distinguish between 'digitization' and 'digitalization'. The former refers to 'the conversion of information or data from analogue to digital format', while the later refers to 'the application of digital platform for industrial or social purposes' (Brotosusilo and Handayani, 2020). By streamlining the recycling strand, digitalization, which represents a fusion of physical and digital systems and new business models, enables the waste management sector to handle an increasing amount of waste outputs daily. Subsequently, this can expand business models that promote sustainable and responsible consumption through the sharing of goods on digital platforms (De Pascale et al., 2021).

The development and applications of digital technologies can unleash market potentials by promoting new industries in local market that create additional jobs for community. To make people become the center of digitalization, digital platforms need to transform the nature of entrepreneurial processes and outcomes (Nižetić et al., 2020b). In fact, this process reflects incremental paths facilitated by the platforms, as it is less bounded than that in the traditional economy. Conventional process systems are being automatized and digitalized in the era of 4IR, which enables a large volume of the data on the operational process. With digital transformation, companies rethink every business they do from online system to how to interact with customers. While digital technologies are not new, such solutions offer a valuable tool for industries to improve their business performance, productivity, cost effectiveness, and competitive advantages, particularly in the post-Covid-19 era (Padilla-Rivera et al., 2021).

In industries, sorting and recycling represent indispensable parts of waste management. Although a better sorting improves the quality of recyclable fractions and reduces residual waste, the 4IR era brings the need for digitalization in the waste sector so that market players can interact online through digital platforms. The digitalization of waste recycling industry also revolutionizes the waste sector by bringing unprecedented disruption in society that benefits economy and the environment (Kurniawan et al., 2013). With respect to digital economy, new jobs are created for community, while to the environment, digitalization enables information about the materials being recycled to be transparent to manufacturers and recyclers for traceability of waste flow so that they can be recovered for reuse. This optimizes the efficiency of material consumption and eliminates waste to address sustainability challenges

due to the MSW generated (Ranta et al., 2021). As a result, digitalized and intelligent management and decision-making have become a global trend.

Digital solutions also enable a high-quality recycling of production residues in CE, as digitalization can track and indicate a material quality. If its quality matches with the corresponding product, this leads not only to more recyclable materials being consumed, but also less downcycling (Kurniawan et al., 2011). This reduces GHG emissions, greening the environment and contributing to climate change mitigation through net CO_2 savings. Since MSW contains a large fraction of non-biodegradable waste, digitalization not only facilitates waste avoidance, but also uses unavoidable waste as resources. Digital applications not only lower barriers posed by distances, but also solve market imperfections and connect people-to-people for business (Zhao et al., 2020). Considering these factors, the transition towards digitalization in the waste sector is critical for cities to sustain the economy and society (Kurniawan et al., 2022c). Societal acceptance is also essential to enable a high-quality recycling of waste (Ballardini et al., 2021).

As people currently live in a global village, they have to think globally and act locally. What happens in the other parts of the world may affect local situation. For this reason, this study critically evaluated and compared to the global trend of digital transformation in waste recycling industry with respect to type of digital solutions, effectiveness for waste reduction, and societal acceptance (Nižetić et al., 2020b). The three parameters affect the success of a digital transformation in a waste recycling market (Bai and Sutanto, 2002).

In southeast Asian region, adopting digital platforms will contribute 40% of incremental market value by 2030. Digital solutions may increase about US$ 230 billion in outputs and US$ 45 billion of income increase (Roy et al., 2021). The World Economic Forum (WEF) anticipates that a global market value of digital transformation would exceed US$100 trillion by 2025, while a CE could generate a net economic gain of US$ 2.1 trillion per year by 2030 (van Capelleveen et al., 2021). Undertaking a holistic digitalization such as adopting digital solutions and new business models can promote a zero-waste paradigm and economic growth opportunities in the waste industry. It is projected that the market value would reach USD 3.6 billion by 2025 (Rumata and Sastrosubroto, 2020). Due to its growth potential for business, promoting digital transformation in the waste sector is necessary to meet the UN's 2030 Agenda (Wang et al., 2022).

If Indonesia joins the global wave of digital transformation, the resulting economic impact of its digital economy will be US$ 150 billion annually by 2025, or about 10% of its current GDP (Liu, 2018). The prize is too large to be ignored by policy-makers and techno-preneurs. This value will make its digital economy become the largest in Southeast Asia region. By moving towards digitalization, it is projected that the country's waste recycling industry would create over 120,000 new jobs and absorb about 3.3 million informal workers such as waste collectors (Smol et al., 2020).

3.7. Implication of digitalization on local waste management industry

Recently, the 4th Industrial Revolution has been linked with intense digitalization through a transformation of industrial sector using IoT technologies. Several countries pursue their strategies to lead a digitalization wave. Germany and the USA promoted a digital-enabled transformation of traditional practices in manufacturing, while China accelerates the development of 5G and cloud computing (Zhu et al., 2021).

Unlike those countries, Indonesia is in the nascent stage of digitalization. Although its netizens are active and it has a vibrant ecosystem for start-ups, Indonesia lags behind in harnessing the benefits of digitalization in the waste sector. Its ICT infrastructure is not sophisticated yet and digital users are not even within the sectors. Despite its users are tech-savvy, digital penetration into business practices is low. Briefly, Indonesia's transformation towards digitalization is still in the transition (Pascual et al., 2017).

Transition pathways is a means to analyze future directions towards a low carbon future in the waste sector (Kurniawan et al., 2010). Digital technologies offer an efficient way of reshaping processes in waste recycling not only to replicate the service digitally, but also to make it time-efficient. The mitigation pathways and their outcomes could bring either positive or negative consequences. Although digitalization helps protect the environment (Díaz-López et al., 2021), the risks are related to potential failures when implementing the chosen pathways. Therefore, the risks often lead to trade-offs between achieving socio-economic, political and environmental goals (Fig. S14) (Schalkwyk et al., 2018).

In terms of social aspects, digital transformation in waste sector has tangible social benefits on customers not only by better informing users/consumers' options or by facilitating waste separation at sources. This transition promotes a shift from linear economy to a CE (Al-Salem et al., 2009). Less waste is generated due to the massive deployment of a waste infrastructure for reuse and repair. Upcycling drives the CE movement to add value to materials that could be recirculated in the system not only in the recycled or recovered forms, but also in the development of advanced materials that could be used in potential recuperative and restorative returns.

From technological points of view, the advantages are obvious such as less costs, enhanced searchability, less work, and fewer errors if a piece of information posted on the website is used repeatedly. The information disseminated via digital platforms influenced business activities and decision-making of customers. The digitalization boosts productivity across sectors and expands public participation in the economy sector (Chauhan et al., 2022). Indonesia has to work on ICT infrastructure components such as high-speed *Wi-Fi* networks and high-density internet access points. As digitalization relies on connectivity, network infrastructure, and interfaces, they are pivotal to enhance data transmission and interoperability of various systems and applications (Gautam et al., 2021).

Although software solutions are available for the tasks such as *i-Pak*, there is a special software for single tasks, while software packages cover an overall process (Madima et al., 2020). Despite interfaces and compatibility between software solutions are important, accounting tasks have not completely developed in the *Rapel* app. Although the app has been integrated in the local waste management, it still requires improvements to secure an efficient market and adoptable services for end-users in the local waste recycling industry (Schwidrowski, 2006).

In addition, there is public concern about data safety and privacy protection. While a regular upgrade of the *app* facilitates the use of customer data, it may open the possibility of increasing risks that their data could be illegally stolen, or misused. Therefore, a free flow of data must be safeguarded, as customers' data have become the backbone of digital economy. In spite of their limitations, the app is a good starting point for the community to reduce their non-biodegradable waste in the framework of CE (Ji et al., 2013).

Despite the fact that shifting towards CE-based digitalization is not easy for business, undoubtedly this leads to immense benefits for economy and the environment. With respect to economic aspects, digital technologies represent an important asset to move waste recycling industry towards a sustainable materials management (Aguilar-Hernandez et al., 2021). Digitalization not only shortens waste collection through route planning, data analytics, and communication between waste generators and waste collectors, but also improves recycling process. Producers facilitates the use of recyclates in manufacturing, while consumers make better purchasing options and sorting decisions, and recyclers enhance waste sourcing (Bjørnbet et al., 2021).

Concerning environmental benefits, a digital transformation in the waste recycling industry not only promotes 3Rs scheme in waste management, but also transforms public services, while providing accurate information, knowledge, and data for public access (Xiao et al., 2018). The built-in sensors of the mobile devices enable data such as position or

functionalities such as QR-Codes, or images to integrate. The success of digitalization based environmental mitigation pathways depend on their implementation (Díaz-López et al., 2021). Digitalization in waste sector would promote sustainability by considering footprints on the environment, as people navigate the transition towards a digital society (Wang et al., 2021).

The implementation of digital technologies in the waste sector also has led to a transformation in cost structure, which influences both technological and financial choices. Although efficiency is enhanced with a lower operational cost for manpower (OPEX), traditionally investment costs (CAPEX) for such digital solutions are high. Therefore, OPEX shifts to CAPEX that favors large private investors (Baars et al., 2021). With large corpus and balance sheets, company can timely infuse scalable investments vis-à-vis technology (R&D) and capital to adopt new technologies fast (Boyer et al., 2021).

In the political domain, large investments by public companies can turn volatile due to political criticism to their organizations' leaders. Therefore, public enterprises are cautious to invest necessary capital costs (Cao et al., 2016). A heavy initial cost riddle can be counteracted by applying "pay-per-use" models that are commonly used in the digital sector (Kanchi et al., 2018).

Different digital solutions can prevent monopolies and platform businesses where they do not benefit innovation, progress, and economic welfare. As digitalization just moves to market adoption in the city, it is not technically feasible to quantify their impacts at macroeconomic level (Delvoie and Plessis-Fraissar, 2005). Although digitalization has the capacity to benefit sustainability through an efficiency improvement, they also bring challenges. While digitalization promotes opportunities for waste business, waste collectors, and waste sellers to engage in recycling activity in the long-term, it is anticipated that technology would replace workers in doing certain industrial assignment. Subsequently, this enhances the gaps between access and application, leading to a greater inequality (Cao et al., 2016).

To minimize this inequality, stakeholders need to enlarge women's access to digital economy for broadening the opportunities for female entrepreneurs to work and earn incomes. Woman empowerment through digital technologies fosters their upward mobility beyond informal sector, and the subsistence levels. This would benefit their families as a whole. For this purpose, the existence of legislative and cultural barriers that prevents women from being benefited by the opportunities need to be removed (Xiao et al., 2018). Other their challenges in achieving the digitalization in waste management include technical capabilities, political conditions, institutional capacities, and social issues (Lebreton and Andrady, 2019).

As its social impacts, the research outcomes of the work would promote a digital society, where digitalization-based urban services enable all residents to equally share the access and benefits of the Information Age (Matthew and Tan, 2016). The efforts need to be directed at ensuring the resilience of communities as the world strives to overcome the challenges due to the global pandemic. As people become the center of digital transformation, future studies need to investigate market mechanisms, competition, and economic incentives essential to promote and expand digitalization in the waste recycling industry. For this purpose, coherent and incisive insights are required to address inequitable opportunity, access, knowledge, and skill of digitalization in waste recycling (El-Wali et al., 2021).

4. Conclusions

Considering the importance of digitalization to foster sustainability through waste recycling, this study has demonstrated its novelty with respect to: (1) how traditional waste management in the developing world can be benefited from digitalization-enabled connectivity platform, and (2) how the digital solution-based platforms drive environmental sustainability based on the CP paradigm. It is evident that the waste sector in Indonesia has been in a transition by moving towards a digitalization. The digitalization has created new opportunities for the CP paradigm to prevent, minimize, and recycle waste from specific waste streams not only to promote resource recovery through a CE, but also to provide secondary raw materials with high quality for waste recycling market, lessening environmental pollution due to non-biodegradable waste.

It is conclusive from this study that public participation, societal acceptance and their engagement with digitalization platform represent key solutions to overcome waste management problems. As the world rapidly becomes digital, stakeholders must work together, collaborate and pool resources to ensure that no one is left behind. To succeed, this requires governments to adopt digital transformation with effective policy actions. Governments need to collaborate with private sector, academia, and society to address key issues on digital transformation in the waste recycling industry. Their collaborations not only strengthen the CP paradigm through resources recovery, but also contribute to sound scientific information for policy-making processes on the roles of digitalization for waste recycling at the end of a product's lifecycle.

As a driving force of social innovation, it was also found that the digital transformation of waste business encouraged local community to commercialize non-biodegradable waste online via the *Rapel* app installed in their smartphones. The app represented a virtual marketplace for recycled materials and/or recyclable products nationwide.

As the implications of this study, the digitalization has created new jobs for about 780 waste collectors in the city (@20 persons/subdistrict). The digitalization of non-biodegradable waste also promoted waste avoidance up to 65%, contributing to 0.2 million Mt of GHG avoidance from local landfills annually. Potential monthly turnover from the waste recycling's transaction through the app was about US$ 2,000/waste bank. The findings reveal that the digital transformation not only has facilitated the recovery of non-biodegradable waste for promoting a CE in the developing world, but also enabled community to do online transactions of recycled goods through a mobile-based application. By moving towards digitalization, it is projected that the country's waste recycling industry would create over 120,000 new jobs and absorb about 3.3 million informal workers such as waste collectors.

CRediT authorship contribution statement

Tonni Agustiono Kurniawan: Responsible for overall investigation, Writing – original draft, Writing – review & editing. **Mohd Hafiz Dzarfan Othman:** Responsible for conceptual and validation, funding acquisition and administration. **Goh Hui Hwang:** Responsible for project administration, project supervision. **Petros Gikas:** Responsible for funding acquisition and data collection, 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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.131911.

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