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Review

Enhancement of Municipal Solid Waste Management in Hong Kong through Innovative Solutions: A Review

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Abstract: With the world population having reached 8 billion people, waste generation is expected to continue its growth in the coming years. Solid waste management (SWM) is an essential part of sustainable development that aims to minimize adverse environmental impacts. Although waste problems have been monitored for decades, some regions still struggle to achieve their sustainability goals in this area. In particular, Hong Kong is still affected by overloaded landfills, with an average daily disposal of 14,739 tonnes. The major waste category is municipal solid waste (MSW), which originates from households and commercial activities. This paper provides an overview of the current SWM strategies and the advancement of technologies adopted in the SWM industry. Supported by a comprehensive literature review, this paper identifies the challenges of SWM in Hong Kong and suggests possible solutions. The findings lead to the direction of future research, which should include innovative solutions for improving recycling behaviors. Adopting technologies such as virtual reality on education platforms and developing mobile applications with a theme of SWM could promote a stronger awareness of waste reduction and recycling among the public.

Keywords: municipal solid waste management; technology adoption; environmental awareness; waste recycling

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1. Introduction

With the rapid rate of urbanization and industrial development, solid waste management has become a worldwide issue among different countries. In 2015, the United Nations (UN) launched the 2030 Agenda for Sustainable Development [1], which set out 17 sustainable development goals for all countries to improve the global scale of development. One of the development goals is ensuring sustainable consumption and recycling patterns, which critically highlights the importance of proactively reducing waste generation. Local governments and companies across different countries are encouraged to practice sustainability through prevention, reduction, recycling and reuse. In this development direction, environmentally sound technologies and management are identified as useful tools that can be used to minimize the pollution and other negative impacts of waste generated by human activities on the environment.

Globally, there is an upward trend in the generation of solid waste around the world. The amount of solid waste generated annually is predicted to expand to 2.59 billion tonnes in 2030 and continue its growth to 3.40 billion tonnes by 2050 [2]. In particular, the region of East Asia and the Pacific was the largest waste generator in 2016 and is predicted to have the highest solid waste generation in the future, with the largest estimated amounts for both 2030 and 2050. This reflects the impacts of waste resulting from the economic activities and significant urban population in the region.

Solid waste is considered as unwanted or useless materials left over from human activities. Although it is mostly in the solid state, it can also be in the form of liquid as sludge [3]. There are three main categories of solid waste. The first type is municipal solid waste, including domestic waste, which is collected in households and public areas, as well as commercial and industrial waste, which is produced from the activities of the business sector (such as shops, restaurants and hotels). The second type is overall construction waste, which is composed of the waste and surplus materials resulting from construction activities. The third type is special waste that requires special disposal arrangements or handling due to its size, quantity and/or physical or chemical characteristics. For example, animal carcasses, treated medical waste and sewage sludge are special types of waste which require special disposal methods to protect the public and the environment from contamination.

For the purpose of minimizing waste generation and its adverse impacts on the environment and public health, the European Union (EU) has regularly amended the Waste Framework Directive, which was first proposed in 1975 [4,5]. A five-step 'waste hierarchy' was established as part of the directive to suggest the order of priority for waste prevention (see Figure 1). The waste hierarchy comprises (i) prevention, (ii) preparation for re-use, (iii) recycling, (iv) recovery and (v) disposal. This order of preference indicates that prevention is the preferred option, and waste disposal at landfills should be the last resort. While this waste hierarchy should be used as the basic principle for the local government's legislation and policy, a collective effort among countries is required to implement the regulations for managing solid waste. The strategies of developed, developing and under-developed countries should be adjusted based on their situations and resources. For instance, some developed countries may invest in waste-to-energy incinerators or technologies, while some under-developed countries may need to prevent open, illegal dumping [6]. Nevertheless, all countries should regularly review their strategies based on the principle of protecting the environment and public health.

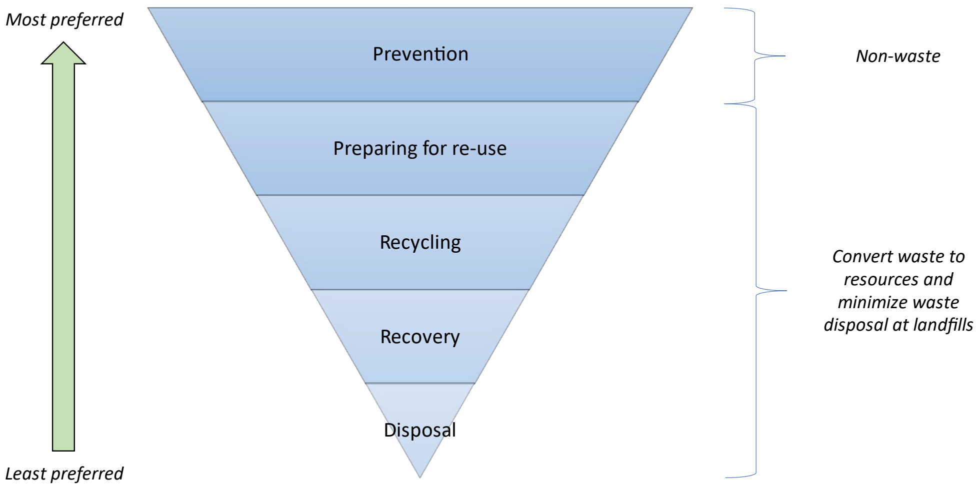

Figure 1. The five-step 'waste hierarchy' of the European Union Waste Framework Directive.

Solid waste management (SWM) refers to the process of handling waste or items that could become waste [3]. The whole process resembles the product life cycle, including collection, processing, transportation and disposal. Poor SWM can result in various adverse impacts such as ocean contamination, the spread of disease and risk of respiratory problems due to improper waste treatment. In some under-developed countries, the unprofessional handling of waste could even pose direct, intermediate health risks to the waste operators and neighborhoods [7]. Conversely, a well-designed SWM endorses the sustainability of the overall system based on scientific evidence (e.g., life cycle assessment) to minimize the negative impacts of waste [8,9]. Additionally, with the concept of a circular economy, a sustainable SWM is also capable of adding secondary materials into the production cycle by reuse and recycling. This brings economic benefits by avoiding the use of primary materials and extending the life cycle of materials in the production cycle [9].

In Hong Kong, around 7% of greenhouse gases are caused by wastes [10], mainly due to the emissions released during the decomposition of solid waste in landfills. The

Environmental Protection Department (EPD) of the government of Hong Kong is responsible for overseeing waste management. In 2021, the annual expenditure of the EPD was HKD 7.324 billion, with 33.7% (around HKD 2.468 billion) spent on the operation of waste management facilities across the city [11]. The government has also established the Hong Kong's Climate Action Plan 2050, which established the long-term vision and goal of sustainable development [12]. One of the areas of focus of the Plan is the transition towards carbon neutrality through waste reduction (to reduce carbon emissions). The reliance on landfills must be reduced by developing waste-to-energy facilities and promoting waste reduction and the recycling of municipal solid waste.

According to the Environment Bureau [13], the municipal solid waste (MSW) generated in Hong Kong decreased by 18% from 6.93 million tonnes in 2010 to 5.67 million tonnes in 2019 (see Figure 2). However, since China banned the importation of 24 types of solid waste (including plastics and papers) in 2017, the recycling industry around the world and in Hong Kong has been greatly impacted, with decreases in capacity and the price of recyclables. During the period of 2010–2019, the amount of MSW recycled locally in Hong Kong also decreased from 3.6 million tonnes to 1.64 million tonnes. Consequently, the amount of MSW disposed at landfills increased during this period. This showed that Hong Kong needs to adopt new approaches to the SWM strategies of the city.

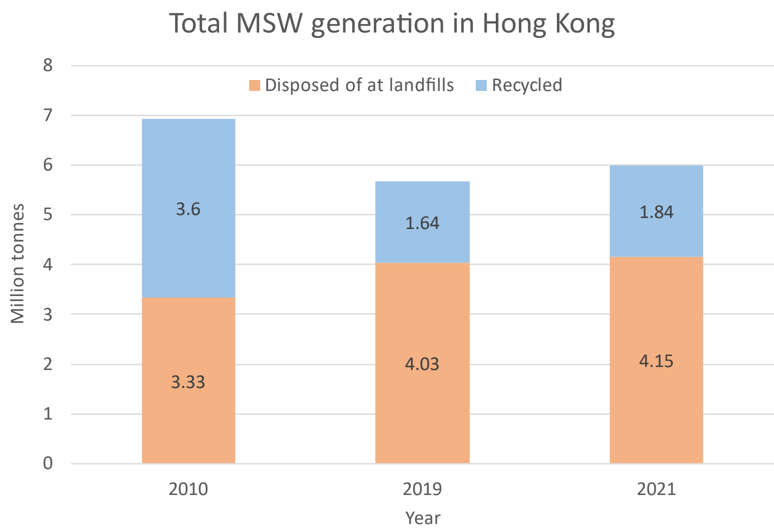

Figure 2. Total municipal solid waste (MSW) generation in years 2010, 2019 and 2021 in Hong Kong.

Research Motivation

In addition to the macro-data over the decade 2010–2019 mentioned above, the MSW issue has still faced ongoing challenges in recent years. As reported by the Environmental Protection Department [14], the disposal rate in Hong Kong was 1.44 kg/person/day in 2020, and the major component of MSW was domestic waste. Considering the influence of the COVID-19 pandemic (including a reduction in economic activities), the disposal of domestic waste increased by 4.4% in 2020 as compared to 2019. This can be partly attributed to people spending more time at home to work and eat during the pandemic.

This revealed that the behaviors of individuals can greatly shape the level of MSW generation, which is a key area for resolving the SWM issues in the city. It is, therefore, important to review the current situation of SWM in Hong Kong so as to explore the possibilities of improving the waste problem. The contributions of this paper include the following:

- An overview of solid waste management (SWM) in Hong Kong, including the existing strategies and the available facilities or services for waste reduction and recycling.
- Review of the applications of advanced technologies for SWM, such as the Internet of Things (IoT), artificial intelligence (AI) and other smart applications.

- Identification of the current challenges regarding SWM in Hong Kong and the possible solution of adopting advanced technologies in the public and private sectors.
- Discussing the future research directions for improving the effectiveness of SWM and waste reduction and recycling practices.

These contributions were achieved by performing a critical review of the recent development of SWM (in both the public and private sectors). During the investigation of this topic, the current challenges were identified and led us to determine the future research directions.

This paper is organized as: Section 2 provides insight into the existing strategies of SWM in Hong Kong, including the facilities accessible to the public. Section 3 presents the applications of advanced technologies for SWM. Section 4 highlights the challenges identified in the review and suggests the possible solutions. Lastly, the paper is concluded in Section 5 with an evaluative discussions of the research outcomes.

2. Existing Strategies of Solid Waste Management in Hong Kong

With the urban development of Hong Kong, the city has become densely populated, with over 7.4 million residents. Due to the limited land resources, there are only three strategic landfills in the city functioning as key disposal sites (including the Northeast, Southeast and West New Territories Landfills). The landfill problems have been a concern since the 2010s, and the landfills are nearing saturation with the vast amount of waste [15]. However, the city has continued to rely on disposal at landfills due to the lack of recycling facilities, and the restraining measures have been ineffective.

There are three main categories of waste classification in Hong Kong, namely overall construction waste, special waste and municipal solid waste (MSW). This article focuses on the MSW, which accounts for most of the total landfill-disposed waste in Hong Kong (more than 70%). MSW includes domestic wastes and commercial and industrial wastes generated by the public. For example, food waste, plastics and paper are common types of MSW, together with other types such as metals, textiles and wood. If the unwanted items of the public are not recycled or recovered, they will be treated as wastes and disposed of at landfills. Due to the dense population and the high level of economic activity in Hong Kong, there is a serious landfill problem, with more than 10,000 tonnes of wastes disposed of at landfills per day.

According to the statistics provided by the Environmental Protection Department [16], more than half of the MSW disposed of at landfills is domestic waste, while the rest is commercial and industrial (C&I) waste. In the case of domestic waste, the major waste type is putrescibles (accounting for 35.9% in 2021), which mostly includes food waste. The domestic waste type with the second highest disposal rate is plastics (accounting for 19.2% in 2021), which consists of plastic bags, plastic bottles and polyfoam dining ware. Putrescibles and plastics are also the leading waste types among C&I wastes. Considering the total MSW, these two waste types formed 52.9% of the total MSW subjected to landfill disposal with more than 6000 tonnes of average daily quantity in 2021. Other waste types with lower disposal quantities include glass, metals, paper, textiles, wood and hazardous household wastes. Altogether, the landfills produced an average of 11,358 tonnes of waste per day in 2021, which is contributing to the saturation of landfills in Hong Kong.

The landfill crisis has worsened since China's waste import ban. China had been importing solid waste from around the world for recycling purposes since 1992 until 2017, when the government of China banned the importation of 24 types of solid waste (including plastic, unsorted paper and discarded textile materials) [17]. This policy has affected the recycling industry around the world, especially in Asia. Under the effects of the waste ban, an estimated cumulative 111 million metric tonnes of plastic waste are projected to be displaced by 2030 [18].

Before China's waste ban, the local recyclers in Hong Kong acted more in the manner of "waste collectors and traders", as they exported most of the recovered waste (approximately two thirds estimated by weight) to the Mainland for further processing [19]. Hong Kong has mainly acted as an entry point for China's importation of recyclable waste, such as plastic waste. In 2016, most of the plastic waste (63%) imported into Hong Kong was transferred directly to China. As mainland China has completely banned importation, the government of Hong Kong has established strategies to support the development of local recycling companies. For example, the Environmental Protection Department (EPD) enhanced the control of wastepaper imports and exports to ban the import of wastepaper into Hong Kong and strictly control the export and re-export of wastepaper [20].

The reduced exporting capacity has urged the government of Hong Kong to strengthen its recycling and other SWM measures. To establish the directions of SWM, the EPD is the key government department that aims to plan, organize and execute the SWM strategy in Hong Kong. The following programs are the major measures that were recently developed for managing domestic solid wastes in the city.

2.1. Green Community Recycling Network

The Green Community Recycling Network, a solid waste recycling scheme under the EPD, aims to collect recyclables and educate the public on waste reduction and recycling. The network is divided into three types of outlets, which are in the forms of stations, stores and spots. The network receives at least eight types of recyclables, including the common types, such as plastics, glass bottles, papers and metals.

The EPD has developed mobile applications for recycling services, enabling the public to engage in recycling activities, namely 'Waste Less' and 'GREEN$'. 'Waste Less' is a mobile application that provides details of more than 7000 recyclable collection points for the disposal usual waste generated in daily life (e.g., wastepaper, metals, plastics, glass bottles, rechargeable batteries and waste electrical and electronic equipment). It also has other functions, such as news broadcasting, diary entry (for recycling efforts) and the provision of knowledge regarding waste reduction and recovery practices. Moreover, 'GREEN$' is a mobile application that is primarily used to introduce the public to the GREEN$ Electronic Participation Incentive Scheme (ePIS) using smartphones. By taking eight types of recyclables to the community recycling networks and the collection points for clean recycling, users can earn points to redeem small gifts under an individual or family QR code [21].

2.2. Municipal Solid Waste (MSW) Charging

In 2018, the Charging for Municipal Solid Waste (Amendment) Bill was tabled by the Legislative Council (LegCo) for scrutiny, and subsequently, it was passed by the LegCo in 2021. It is prepared to progress towards implementation in the second half of 2023 at the earliest. MSW charging is employed as a waste reduction strategy that enforces the financial incentives and legal responsibilities necessary to drive behavioral changes among all citizens and businesses in order to reduce waste. With the 'polluter pays' principle, the waste producer must bear the cost of disposing the waste based on the quantity. There are two modes of MSW charging, namely, (i) charging by designated rubbish bags or labels, which applies to most of the general public, and (ii) charging by weight, which is applicable to private waste collectors [22].

2.3. Reverse Vending Machine (RVM) Polit Scheme

The EPD launched a pilot scheme to provide 60 reverse vending machines (RVMs) to government facilities in 2021, and the total number of RVMs across the city doubled in 2022. Figure 3 illustrates the concept of the RVMs. The public can bring their used plastic beverage containers and, if accepted by the RVM, they can select either to receive an instant rebate (HKD 0.1 per container) through an e-payment platform or to donating it to designated charitable organizations. The whole recycling operation is shown on the screen of the RVM, and the public can follow the operation procedures step by step. Once the RVM is full, the contractor automatically receives a signal from the RVM and arranges the collection. The collected bottles are sent to the appointed local recyclers for further recycling. The public can check the real-time capacity of each RVM on the scheme website to avoid brining the recyclables to a full machine [23].

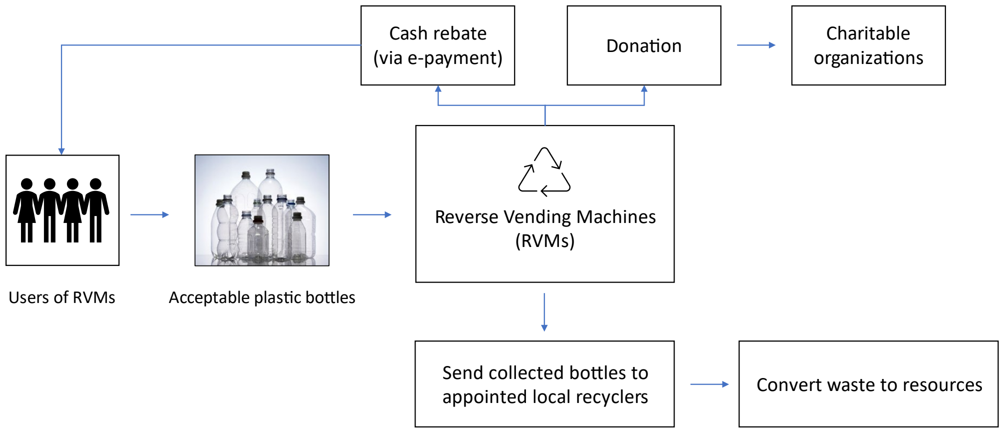

Figure 3. Illustration of the Reverse Vending Machine (RVM) Pilot Scheme in Hong Kong.

In addition to the community programs and the statutory charging scheme, the Hong Kong government launched a project designated as 'Integrated Waste Management Facilities' in 2018. The aim of the facilities is to reduce the size of the MSW generated by the public and decrease the landfill disposal volume. The project is currently under construction and is expected to be commissioned in 2025. The key components of the facilities include waste sorting and recycling, waste heat recovery for power generation, incineration and other environmental education services. Modern incineration technology is the core treatment technology for this project, operating through means such as waste-to-energy methods, moving grates and flue gas cleansing processes.

3. Application of Advanced Technologies for SWM

In light of the upwards trend of solid waste generation, the development of waste management strategies has drawn attention from industries and local governments across the world. More investigation and suggestions have been delivered to improve the efficiency of the operations for waste management, such as landfilling, recycling, material recovery facilities and incineration [24,25]. Moreover, under the framework of smart cities, the innovative approach of intelligent waste management has emerged [26]. According to the European Environment Agency [27], the advanced digital technologies that can be used for improving waste management include robotics, artificial intelligence and neural networks, the Internet of Things, cloud computing and data analytics. By using these technologies to improve data collection, integration and analysis, waste management activities could be tracked more comprehensively so as to generate more innovative solutions.

Technology has been used in numerous ways to facilitate waste management, especially in high-income countries [2]. Using well-developed digital means (such as websites, mobile applications and radio) has been effective in spreading information among citizens about waste management or collection services. As another approach, mobile apps have also been developed to encourage recycling behaviors among the public by gamifying the system and including points and rewards in the 'game' [28,29]. In this way, the users (or players) of these gaming apps are motivated to complete waste recycling actions. Another example is the radio frequency identification (RFID) technology used for the waste pricing system in Korea [30]. The system aims to reduce the waste disposed of by households. Individuals must use a personalized card (with RFID) to open the local food waste bin, and they are charged accordingly based on the weight of the disposed waste.

3.1. Internet of Things (IoT) in SWM

The Internet of Things (IoT) refers to a large network of interconnected objects. It can be described as a network of real-world devices of any type or size (such as smart phones, vehicles, buildings, etc.), and it allows these devices to communicate with each other by regularly collecting data from the objects and sharing the data on the IoT platform [31]. The data collection can be performed by embedding sensors to emit data on the state of the devices. The emitted data are then sent to the IoT platform, which integrates the data and provides a common space for the devices to communicate in. Furthermore, data can be extracted for data visualization and analysis to provide useful information to the users.

When applied to waste management, IoT can be a powerful tool for the development of smart waste management which uses advanced technology to render waste management more efficient. Figure 4 shows an example of the adoption of IoT for waste management, including the use of sensors (usually ultrasonic sensors and weight sensors) to monitor the state of the rubbish bins. The sensors can detect the fill level of the waste bins, and the devices can send real-time data to the IoT platform used by the waste collectors [32]. The data can then be used to compute an optimized route for the drivers of the waste collection trucks. For instance, Evreka [33] (a global SaaS company that focuses on waste management) provides products for monitoring the fullness, temperature and location of waste containers. The data can be integrated into a waste management system using other software solutions. The users can keep track of the status on the system that gathers the data and sends timely notifications to the users in cases of abnormality.

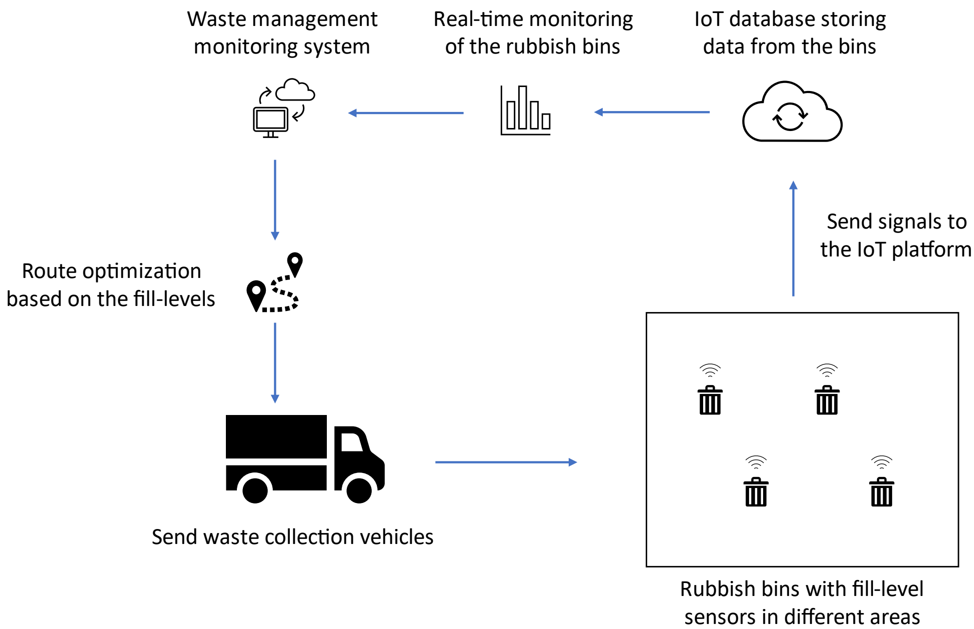

Figure 4. Application of the Internet of Things (IoT) to waste collection services.

One of the advantages of using IoT in waste management systems (or smart waste management) is the increase in operational efficiency [34,35]. For waste collection, the waste collectors can establish a dashboard to monitor the bins remotely. When the fill levels of the bins are constantly monitored, the waste collectors can reduce the time they spend checking the bins manually or pre-plan their transportation routes. This can save them time, manpower and money (e.g., fuel costs for the trucks) when collecting the waste from the community and allows them to re-allocate their resources accordingly. Another advantage of smart waste management is the enhancement of the users' (or customers') satisfaction. With the system monitoring the waste bins through capacity sensors, there is less chance of overflowing or missed pick-up and, therefore, a more hygienic environment or neighborhood can be created.

3.2. Artificial Intelligence (AI) in SWM

Artificial intelligence (AI) refers to machines or computers that stimulate the human mind and intimate the cognitive functions deriving from human intelligence [36–38]. It gathers functional technologies and computational methods to simulate human intelligence by enabling the machines to detect, comprehend, execute and learn. It is capable of learning from previous experience in order to react to, and provide logical solutions for solving, problems. This technology is becoming more popular, as it benefits operational efficiency by facilitating the design of systems in various fields. It has been widely used in environmental management, government services and the health, finance and manufacturing industries.

As concerns regarding SWM grow, AI is also being adopted to solve SWM problems, especially in developed countries. Andeobu et al. [37] summarized the AI applications that have been used for several aspects of SWM, including waste generation, bin level monitoring, waste sorting, waste collection and vehicle route planning. Using waste sorting as an example, AI applications can be used to scan and identify waste discarded in bins. The sensors or scanners can classify the waste and analyze the categories of waste for segregation. The data can be used for the automatic sorting process. Combined with the manual sorting process, the recycling facilities can develop an optimal hybrid sorting operation accordingly.

Traditionally, the waste sorting process in material recovery facilities (MRFs) has relied on manual picking by the workers, which is inefficient and unstable due to the inconsistent supply of workers. The European Commission [39] highlighted the benefits of using a waste-sorting robot created by ZenRobotics, a Helsinki-based company. The robot has higher speed and efficiency when picking and sorting the waste, as the robot can pick 2000–4000 items per hour, as compared to 200 items in the case of manual picking [40]. Robots may also work in ways that are undesirable for traditional sorting methods and are designed to be far more productive, working for 24 h per day, lifting heavy objects and handling hazardous waste.

4. Challenges of SWM in Hong Kong and Possible Solutions

Although the HKSAR government has established several SWM programs, the overloaded landfills are still concerning for the wider community. The amount of solid waste is expected to grow in the coming years due to the increasing population. To meet their long-term needs, the Environmental Protection Department (EPD) is proceeding with extension plans aiming to increase the capacity of the existing landfills. However, the over-reliance on landfills must be diminished, as suggested in the Waste Blueprint for Hong Kong 2035 [13]. At the same time, the coverage of sustainable SWM plans must be more thorough in order to address the constantly increasing demands for a good quality of life and environmental protection. The following issues cover the challenges facing SWM in Hong Kong and the possible solutions for improvement.

4.1. Ineffective Regulatory Policies

In 2013, the Environment Bureau of the Hong Kong government published the Hong Kong Blueprint For Sustainable Use of Resources 2013–2022 [41]. At that time, the waste generation in Hong Kong already appeared to be a problem, with a high per capita MSW disposal rate as compared to other Asian cities. The Blueprint addressed this problem by setting targets for waste reduction. Based on the per capita MSW disposal rate of 1.27 kg in 2021, the targets were set as 1.0 kg for 2017 and 0.8 kg for 2022. However, the target for 2017 was not met, as the reported per capita MSW disposal rate was 1.45 kg [14]. In the reported period from 2011 to 2020, the MSW disposal rate in 2011 was the lowest, with the rates in the following 9 years ranging from 1.30 kg to 1.53 kg per capita. The latest data show that the MSW disposal rate is 1.44 kg per capita, which is far higher than the target of 0.8 kg. Later, in 2021, the Environment Bureau [13] published an updated blueprint to reduce the MSW disposal rate by 40–45% upon the implementation of the MSW charges.

As covered in Section 2, new SWM programs have been developed in Hong Kong, such as the MSW charging scheme, Green Community Recycling Network and the Reverse Vending Machines Pilot Scheme. Although the schemes have been introduced into the community, these ideas are relatively new and involve several challenges when they are implemented. The participation of the public is limited due to the likelihood that they will avoid the procedures when possible. In a previous study conducted in China [42], it was reported that the fundamental barriers to using smart technologies for waste management are the insufficiency of regulatory pressures and the lack of market demand and pressure. The government, waste management companies and the relevant organizations are the key stakeholders in driving smart waste management. Since knowledge about environmental protection among the public may be inadequate in some regions (e.g., littering is common), the economic benefits of investing in smart waste management are uncertain for the market. To address this issue, the government plays a significant role in order to strengthen its enforcement of the relevant regulations.

In Hong Kong, the preparatory work of the MSW charging scheme has begun to prepare stakeholders (especially the public) for its implementation. Although the charging scheme has already created a strong financial incentive for the citizens to reduce their waste generation, the perception of the public is another factor that could strengthen its efficacy. The perceived fairness and effectiveness of waste charging may reflect the attitude of the public and their degree of support for the purpose of waste reduction [43]. The public tend to be more supportive when they are convinced that the policies are fair and effective. For example, the local citizens have been frustrated after seeing video clips of cleaners mixing recyclables in separate recycling bins. This created a perception that their recycling effort is wasteful and the policy is unregulated. For the success of the charging scheme, the government of Hong Kong will have to strictly supervise their upcoming policies with transparency in order to build up the confidence of the public.

Due to the barriers to the current waste management strategies, the approach tends to follow the traditional policies, and the evolution is subsequently slow. With the on-going development of society, more types and higher amounts of MSW have been generated, with an increasing trend. Authorities are encouraged to adopt modern technologies to restrain the negative impacts of ineffective waste management systems. There are potential improvements to be gained by enhancing various stages of waste management, such as waste collection, source segregation and recycling, to eventually save energy or reduce the emissions of greenhouse gases [44]. Examples of innovative technologies include web-based geographic information system technology, automatic selection processes for used bottles and automated sorting [45]. These technologies could be integrated into the development of a smart city to improve the overall efficiency.

4.2. Lack of Technology Adoption in SWM

While the new technologies could bring financial benefits and improve the efficiency of the SWM practices, the initial costs required for introducing the new systems are high. For IoT-based systems, the companies or government need to purchase the devices or sensors for data collection. Meanwhile, the development of the software (i.e., the IoT platform) can be complex and requires the refinement of the designs by professionals to ensure that the system is operating properly and providing correct, useful information. Since the system is complex and interconnected, a failure of one part of the system may lead to the failure of the entire system. Careful trial-and-error testing is required during the development of the system by the programming professionals, which can be costly. Another consideration is that, with the system maturing in the long term, this may increase unemployment for unskilled workers as manpower requirements decrease.

Moreover, AI is still underutilized in waste management due to its intensive use of energy during the initial training process. When the waste is disposed of and mixed together with diverse types of materials, the image shown to the AI system will usually include intrusive background or 'noise' [46]. This renders the item in the image difficult to recognize or classify and, thus, lengthens the learning process of the system. Yet, with more data on real-world rubbish being collected and analyzed, the speed and accuracy of automated waste sorting is expected to improve over time. The companies will then be able to reduce their operation costs and develop an optimal sorting process.

Despite the fact that the initial investment would be costly, the inclusion of technologies such as IoT and AI could significantly reduce the number of workers required for the SWM practices. The current SWM approach mostly involves a fixed collection timetable and inconsistent disposal performed by individuals in residential or public areas. This means that the collectors must check the bins manually to see whether it is full and needs clearing, especially in outdoor public spaces, where the usage pattern is irregular [47]. With the help of IoT technology, the real-time state of the rubbish bins can be monitored through the system, and the data can be used to generate waste analysis for different stakeholders [48].

Additionally, a highly automated waste management system based on AI technologies could significantly reduce the requirement for workers in the SWM facilities. In addition to keeping humans away from the undesirable working environment, the robotic system could also lower the chance of injuries and need for single-use equipment (such as gloves) and improve the operational efficiency. With the wider adoption of these smart systems, the data generated could be translated into important statistics for observing the patterns of the MSW. The data could then be analyzed and used as a basis for future planning in the SWM industry (e.g., performing the route optimization of waste collection trucks to cut operating costs). By introducing the advanced technologies for SWM, together with other technologies, such as cloud and data analytics, the information could be frequently updated and utilized to raise public awareness. For example, generating monthly reports on the types of sorted waste may encourage the public to deliberately reduce their use of certain products. The data on waste collection would also be useful for the public, helping them to bring their waste to the right location at the right time.

4.3. Low Recycling Rate

In recent years, more recyclables have been recovered from the MSW at the local recycling facilities in Hong Kong [14]. However, the local recycling industries are underdeveloped due to the economic structure of the city. As a result, the recovered materials are usually delivered to other countries or regions with more demanding recycling industries. Over 80% of the recovered materials in Hong Kong are exported for further handling or recycling. This has created a strong dependence on the market conditions of the destination regions. The importation policy (e.g., China's waste ban) significantly affects the chain of the recyclables within the city and, eventually, the recycling rate. Therefore, source reduction is crucial for reducing the overwhelming amount of waste.

Waste separation at the source has been considered an effective approach for increasing the recovery rate and has environmental and economic benefits [49,50]. A higher quality of the separated recyclables is more likely to result in recovered materials and, hence, less waste is sent for landfill disposal. For this source separation to be functional, a collective effort and commitment of individuals among the public is required. The general public tend to be more proactive in recycling when they can conveniently access the recycling facilities and the economic and environmental benefits. Although the HKSAR government has launched recycling services (such as GREEN@COMMUNITY) for the public to facilitate their recycling behaviors, the engagement of the community seems to be lacking due to the culture of convenience in the city. These services are still underutilized by a considerable part of society because of their fast-paced lifestyles. It has even been reported that the RVMs are misused and quickly filled up with unclean and unwanted materials. Even with a fairly high educational level and standard of living, environmental awareness among the public must be raised for the people's preference to transition from short-term convenience to sustainability [51].

As Hong Kong is approaching the implementation period of the waste charging scheme, the awareness and publicity of waste reduction or recycling should be raised. The financial implications of the 'polluter pays' principle should suppress waste generation in households. With effective communication with the users of waste management services, responsible behaviors can be encouraged among communities (e.g., waste sorting at home) to change the culture of handling MSW in the city. The government is, therefore, responsible for planning strategies to interact with the public and provide more suitable services based on the review of the progress in order to enhance the overall waste management performance.

4.4. Low Awareness of Waste Handling Culture and Ethics

Public awareness of waste handling is a significant factor for waste recycling and reduction in the community. The Consumer Council [52] conducted a baseline survey in 2015 and a tracking survey in 2020 about sustainable consumption in Hong Kong. The report presented the sustainable consumption index (SCI) for the public's awareness, attitudes and behaviors and, lastly, readiness to adopt sustainable consumption. As compared to the baseline study, the SCI of consumers' awareness of, and attitude towards, waste separation increased from 73 to 77, which means that the consumers became more mindful of the benefits of waste separation at home. However, the SCI for the consumers' recycling behavior and readiness was unchanged in the five years, remaining at 63. This shows that there is a gap in strengthening participation in recycling practices.

Citizen engagement is a critical factor for achieving sustainable solid waste management [2]. Education, citizen feedback and financial incentives form an important part of waste management in efforts to engage society so as to raise public awareness and attitudes towards the handling of waste. Building knowledge within the community could result in a positive change in behaviors in reducing waste generation at the source, disposing of waste properly and recycling. The general public should be adequately taught and provided with relevant, correct information or resources that are easily accessible to them. The education campaigns that deliver information on waste separation and recycling should aim to reach most of the public, regardless of age and gender [53].

Information technology is a useful tool for the authorities, enabling them to engage the public. Mobile applications, websites and radio have often been used to distribute information about waste management, such as periodic reports (e.g., annual waste statistics). In the opposite direction of communication, the public can also provide feedback to the corresponding party of the government through online platforms (e.g., reporting illegal dumping). The Green Best Practice Community of the European Commission stated that a well-designed awareness campaign should be able to tackle the two main barriers to recycling, which are (i) the lack of knowledge of waste segregation and (ii) the attitudes of the public towards the avoidance and sorting of waste. With the proper use of the communication channels, there clear messages could be delivered to the public about the services available to them.

Meanwhile, in Hong Kong, the EcoPark created by the Environmental Protection Department serves as a large-scale education resource center on the theme of municipal waste. The EcoPark is equipped with interactive educational facilities, including a 3D model that simulates landfills, a group game zone with motion sensing games and a photo taking zone. It also organizes events and exhibitions to provide useful information to the visitors, enabling them to learn about the correct concepts of SWM. The education center should be regularly updated to provide information to visitors from all social groups, as SWM is the responsibility of everybody in society [54]. It can also serve as a supplement to the school curriculum so as to extend the learning of students.

4.5. Inadequate Educational Platforms for SWM

There are many emerging smart applications, such as the Internet of Things (IoT), sensors and actuators, big data and virtual reality and augmented reality (VAR), which have been applied in different sectors for urban planning and implementation but seldom for SWM and its associated educational platforms. As suggested in the Waste Blueprint for Hong Kong 2035 [13], education and publicity are crucial for achieving waste management goals in Hong Kong. More educational programs and campaigns will be launched in the coming years, which will provide a great opportunity to adopt digital technology and expand the potential of public education.

To encourage the development of behaviors for the management of domestic waste, application-based environmental learning is useful tool for guiding users to complete and repeat certain actions related to waste management. Shan et al. [29] proposed a recycling program using a mobile app to encourage behavioral change in Singapore. The RANAS (risks, attitudes, norms, abilities and self-regulation) approach was used in the design of the mobile app, with features of incentives and rewards (such as the redemption of cash and vouchers). It was suggested that the mobile-app-aided recycling program influenced the users' behaviors and could be used as a training tool in the long term.

On the other hand, the introduction of VAR on the educational or training platforms also has the potential to develop an interactive learning experience. In the past, VAR was mainly applied in entertainment, including video games and television programs. With the advanced emerging technology, VAR has been deployed in industries to stimulate high-risk scenarios and provide a safe training platform for users. In developing smart education and training infrastructure, VAR is able to provide both static visualizations and interactive data visualizations, including gesture-based interaction features. VAR can also be integrated with large screens to support an immersive learning experience, with high-resolution display screens in different contexts of use. When integrated with other platforms, it can provide an extensive environment for the building of an active recycling culture (see Figure 5).

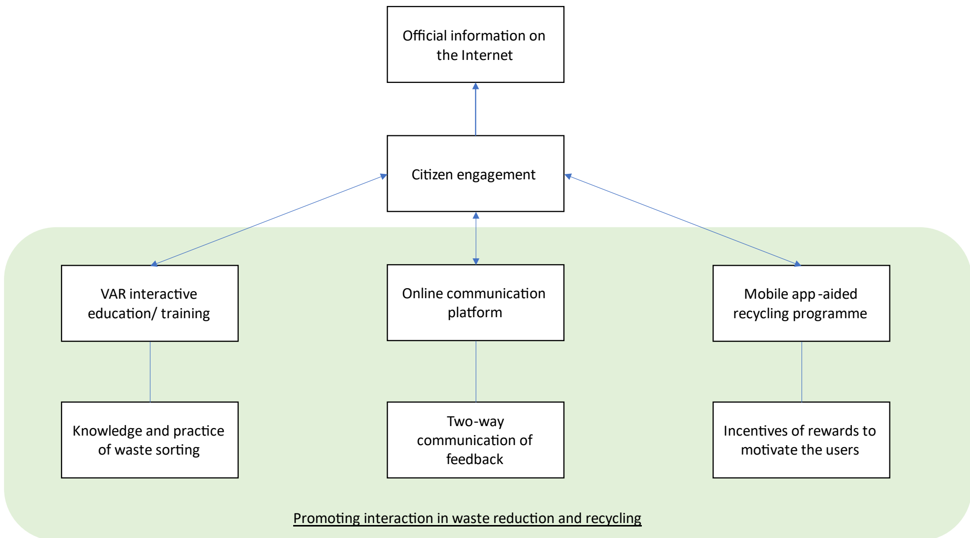

Figure 5. Interactive recycling platforms for engaging citizens.

The market has witnessed the application of VAR on educational platforms for waste management. In 2019, free-to-access virtual reality (VR) video game machines (designed by a company called VitrellaCore) were placed in a public space in Shanghai to simulate a waste sorting experience [55]. The users were encouraged to discard their waste into the correct bin to win points, which taught the users the proper behaviors for handling waste. Likewise, a Slovak company, Moving Environment [56], designed a VR game to simulate waste sorting in front of a sorting line. The game is based on a machine sending different types of objects, and the user needs to separate glass, plastic and paper as fast as possible (including the removal of the packaging). These games provide a more interesting experience for the users, which may be more interactive and unforgettable learning experiences.

The education platforms act as important tools that guide individuals to adopt a sustainable lifestyle. One of the barriers to changing the public's intention to regularly sort their domestic waste is the awareness of the benefits and perceived difficulties [57]. The future development of this technology should involve assessments of the understanding of the users or residents so that the content of the education or training can be more specific in guiding the users and uplifting their attitudes towards sustainable waste handling (e.g., waste sorting at home).

5. Discussion and Conclusions

Based on the background of research on the existing solid waste management (SWM) practices in Hong Kong, this paper provided an overview of SWM in the city and highlights the strategies set out by the local government and the related SWM services. Currently, the HKSAR primarily focuses on waste reduction and recycling to shrink the over-reliance on disposal at landfills. The government has, therefore, introduced schemes for collecting domestic recyclables and charging for MSW to motivate the public to embrace sustainable practices. Nevertheless, due to the emphasis on convenience in the city, with the upcoming improvements, the existing services must be easy to use and widespread across the society so as to raise general participation.

The paper also reviewed the applications of smart technologies in different processes for SWM. Some highlighted technologies, such as IoT and AI, have been used for monitoring the fill level of rubbish bins for waste collection services and automated sorting for the waste segregation process. Although the initial costs of adopting new systems could be high, these technologies would reduce the operational costs by enhancing the efficiency. Furthermore, the SWM working environment may sometimes be undesirable for the workers. This causes an inconsistent supply of workers, but the situation can be improved by replacing their labor with automated handling. The working conditions can then be re-arranged for a better allocation of resources.

The current challenges of SWM in Hong Kong were also revealed. Given the economic background of the city as a financial hub, the development of the local recycling industry is limited. The recyclable wastes generated locally are usually transferred to the mainland for further processing, together with other recyclables imported from overseas into Hong Kong. The change in policies of market outlets has significantly affected the chain of movement and the amount of waste immobilized in the city. Furthermore, the recycling behaviors of the local citizens are weak. The recycling rate and the amount of recycled material are arguably still low. Since citizen engagement is very important for waste reduction (especially for MSW), it should be taken into account for the purpose of improvement in terms of behavioral changes and education.

Future research should be directed towards the development of smart systems that are more interactive and engaging for the public. In order to keep pace with the fast-paced culture of the city, any enhancement should be realized with smart technologies. This paper covered the examples of adopting smart technologies for SWM, behavioral changes and education oriented towards sustainable SWM practices. Since these will be new to the majority of the public, questionnaires or surveys could be conducted prior to the related studies. The Technology Acceptance Model (TAM) could also be considered to evaluate the perception of the general public. By understanding the actual needs and motivation of the community, the effectiveness of the SWM practices could be significantly boosted.

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References

1. United Nations. *Transforming our World: The 2030 Agenda for Sustainable Development*; UN: New York, NY, USA, 2015.
2. Kaza, S.; Yao, L.; Bhada-Tata, P.; Van Woerden, F. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*; World Bank Publications: Washington, DC, USA, 2018.
3. Christensen, T.H. *Solid Waste Technology & Management*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
4. European Commission. *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain DIRECTIVES*; European Commission: Brussels, Belgium, 2008.
5. European Commission. *Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2008/98/EC on Waste*; European Commission: Brussels, Belgium, 2018.
6. Sharma, K.D.; Jain, S. Municipal solid waste generation, composition, and management: The global scenario. *Soc. Responsib. J.* **2020**, *16*, 917–948. [CrossRef]
7. Ziraba, A.K.; Haregu, T.N.; Mberu, B. A review and framework for understanding the potential impact of poor solid waste management on health in developing countries. *Arch. Public Health* **2016**, *74*, 55. [CrossRef]
8. Khandelwal, H.; Dhar, H.; Thalla, A.K.; Kumar, S. Application of life cycle assessment in municipal solid waste management: A worldwide critical review. *J. Clean. Prod.* **2019**, *209*, 630–654. [CrossRef]
9. Das, S.; Lee, S.H.; Kumar, P.; Kim, K.-H.; Lee, S.S.; Bhattacharya, S.S. Solid waste management: Scope and the challenge of sustainability. *J. Clean. Prod.* **2019**, *228*, 658–678. [CrossRef]
10. Legislative Council Secretariat. *Decarbonization Strategy in Hong Kong*; Legislative Council Secretariat: Hong Kong, China, 2022.
11. Environmental Protection Department. *Environmental Performance Report 2022*; Environmental Protection Department: Hong Kong, China, 2022.
12. Hong Kong Special Administrative Region. *Hong Kong's Climate Action Plan 2050*; Environment and Ecology Bureau: Hong Kong, China, 2021.
13. Environment Bureau. *Waste Blueprint for Hong Kong 2035*; Environment Bureau: Hong Kong, China, 2021.
14. Environmental Protection Department. *Monitoring of Solid Waste in Hong Kong 2020*; Environmental Protection Department: Hong Kong, China, 2021.
15. Fabian, N.; Lou, L.I.T. The struggle for sustainable waste management in Hong Kong: 1950s–2010s. *Worldw. Waste: J. Interdiscip. Stud.* **2019**, *2*. [CrossRef]
16. Environmental Protection Department. *Monitoring of Solid Waste in Hong Kong 2021*; Environmental Protection Department: Hong Kong, China, 2022.
17. Qu, S.; Guo, Y.; Ma, Z.; Chen, W.-Q.; Liu, J.; Liu, G.; Wang, Y.; Xu, M. Implications of China's foreign waste ban on the global circular economy. *Resour. Conserv. Recycl.* **2019**, *144*, 252–255. [CrossRef]
18. Brooks, A.L.; Wang, S.; Jambeck, J.R. The Chinese import ban and its impact on global plastic waste trade. *Sci. Adv.* **2018**, *4*, eaat0131. [CrossRef]
19. Legislative Council Secretariat. *Policy Support to the Recycling Industry in Selected Places*; Legislative Council Secretariat: Hong Kong, China, 2019.
20. Environmental Protection Department. *Guidelines on Import and Export Control of Waste Paper*; Environmental Protection Department: Hong Kong, China, 2020.
21. Environmental Protection Department. GREEN@COMMUNITY. Available online: https://www.wastereduction.gov.hk/en/community/crn_intro.htm (accessed on 30 November 2022).
22. Environmental Protection Department. What Is Municipal Solid Waste (MSW) Charging? Available online: https://www.mswcharging.gov.hk/index.php?lang=en (accessed on 12 November 2022).
23. Environmental Protection Department. Reverse Vending Machine Pilot Scheme. Available online: https://www.hkrvm.com.hk/en (accessed on 12 November 2022).
24. Nanda, S.; Berruti, F. Municipal solid waste management and landfilling technologies: A review. *Environ. Chem. Lett.* **2020**, *19*, 1433–1456. [CrossRef]
25. Yaman, C.; Anil, I.; Alagha, O. Potential for greenhouse gas reduction and energy recovery from MSW through different waste management technologies. *J. Clean. Prod.* **2020**, *264*, 121432. [CrossRef]
26. Anagnostopoulos, T.; Zaslavsky, A.; Kolomvatsos, K.; Medvedev, A.; Amirian, P.; Morley, J.; Hadjieftymiades, S. Challenges and opportunities of waste management in IoT-enabled smart cities: A survey. *IEEE Trans. Sustain. Comput.* **2017**, *2*, 275–289. [CrossRef]
27. European Environment Agency. *Digital Technologies Will Deliver More Efficient Waste Management in Europe*; European Environment Agency: Copenhagen, Denmark, 2021.
28. Lidia, A.-C.; Julio, R.-T.; Petra, D.S.-P.; Rafael, P.-J. How to encourage recycling behaviour? The case of WasteApp: A gamified mobile application. *Sustainability* **2018**, *10*, 1544. [CrossRef]
29. Shan, X.; Ang, W.L.; Yang, E.-H. Mobile app-aided risks, attitudes, norms, abilities and self-regulation (RANAS) approach for recycling behavioral change in Singapore. *Resour. Conserv. Recycl.* **2020**, *162*, 105049. [CrossRef]
30. Lee, S.; Jung, K. The role of community-led governance in innovation diffusion: The case of RFID waste pricing system in the Republic of Korea. *Sustainability* **2018**, *10*, 3125. [CrossRef]

31. Patel, K.K.; Patel, S.M. Internet of things-IOT: Definition, characteristics, architecture, enabling technologies, application & future challenges. *Int. J. Eng. Sci. Comput.* **2016**, 6. [CrossRef]
32. Suresh, N.; Limbo, A.; Hashiyana, V.; Ujakpa, M.M.; Nyirenda, C. An Internet of Things (IoT) Based Solid Waste Monitoring System. In Proceedings of the 2nd International Conference on Intelligent and Innovative Computing Applications; ACM: New York, NY, USA, 2020; pp. 1–5.
33. Evreka. Digital solutions for waste, recycling and route management. Available online: https://evreka.co/evreka360/ (accessed on 25 November 2022).
34. Ali, T.; Irfan, M.; Alwadie, A.S.; Glowacz, A. IoT-Based Smart Waste Bin Monitoring and Municipal Solid Waste Management System for Smart Cities. *Arab. J. Sci. Eng.* **2020**, *45*, 10185–10198. [CrossRef]
35. Misra, D.; Das, G.; Chakrabortty, T.; Das, D. An IoT-based waste management system monitored by cloud. *J. Mater. Cycles Waste Manag.* **2018**, *20*, 1574–1582. [CrossRef]
36. Abdallah, M.; Abu Talib, M.; Feroz, S.; Nasir, Q.; Abdalla, H.; Mahfood, B. Artificial intelligence applications in solid waste management: A systematic research review. *Waste Manag.* **2020**, *109*, 231–246. [CrossRef]
37. Andeobu, L.; Wibowo, S.; Grandhi, S. Artificial intelligence applications for sustainable solid waste management practices in Australia: A systematic review. *Sci. Total Environ.* **2022**, *834*, 155389. [CrossRef]
38. Wilts, H.; Garcia, B.R.; Garlito, R.G.; Gómez, L.S.; Prieto, E.G. Artificial Intelligence in the Sorting of Municipal Waste as an Enabler of the Circular Economy. *Resources* **2021**, *10*, 28. [CrossRef]
39. European Commission. *ZenRobotics: Applying Artificial Intelligence to Waste Sorting*; European Commission: Brussels, Belgium, 2021.
40. ZenRobotics. Why does it pay off to robotize your waste operations? Available online: https://www.terex.com/zenrobotics/robots/overview (accessed on 25 November 2022).
41. Environment Bureau. *The Hong Kong Blueprint for Sustainable Use of Resources 2013–2022*; Environment Bureau: Hong Kong, China, 2013.
42. Zhang, A.; Venkatesh, V.G.; Liu, Y.; Wan, M.; Qu, T.; Huisingh, D. Barriers to smart waste management for a circular economy in China. *J. Clean. Prod.* **2019**, *240*, 118198. [CrossRef]
43. Chung, W.; Yeung, I.M.H. Analysis of residents' choice of waste charge methods and willingness to pay amount for solid waste management in Hong Kong. *Waste Manag.* **2019**, *96*, 136–148. [CrossRef]
44. Khan, S.; Anjum, R.; Raza, S.T.; Ahmed Bazai, N.; Ihtisham, M. Technologies for municipal solid waste management: Current status, challenges, and future perspectives. *Chemosphere* **2022**, *288*, 132403. [CrossRef]
45. Goutam Mukherjee, A.; Ramesh Wanjari, U.; Chakraborty, R.; Renu, K.; Vellingiri, B.; George, A.; Rajan, S.C.R.; Valsala Gopalakrishnan, A. A review on modern and smart technologies for efficient waste disposal and management. *J. Environ. Manag.* **2021**, *297*, 113347. [CrossRef]
46. Yang, J.; Zeng, Z.; Wang, K.; Zou, H.; Xie, L. GarbageNet: A unified learning framework for robust garbage classification. *IEEE Trans. Artif. Intell.* **2021**, *2*, 372–380. [CrossRef]
47. Vishnu, S.; Ramson, S.R.; Senith, S.; Anagnostopoulos, T.; Abu-Mahfouz, A.M.; Fan, X.; Srinivasan, S.; Kirubaraj, A.A. IoT-Enabled solid waste management in smart cities. *Smart Cities* **2021**, *4*, 1004–1017. [CrossRef]
48. Samih, H. Smart cities and internet of things. *J. Inf. Technol. Cases Appl.* **2019**, *21*, 3–12. [CrossRef]
49. Calabro, P.S.; Satira, A. Recent advancements toward resilient and sustainable municipal solid waste collection systems. *Curr. Opin. Green Sustain. Chem.* **2020**, *26*, 100375. [CrossRef]
50. De Feo, G.; D'Argenio, F.; Ferrara, C.; Grosso, A. A procedure to assess the environmental, social and economic benefits wasted in the paper and cardboard fraction of the unsorted residual waste. *J. Clean. Prod.* **2021**, *296*, 126566. [CrossRef]
51. Cai, K.; Xie, Y.; Song, Q.; Sheng, N.; Wen, Z. Identifying the status and differences between urban and rural residents' behaviors and attitudes toward express packaging waste management in Guangdong Province, China. *Sci. Total Environ.* **2021**, *797*, 148996. [CrossRef]
52. Consumer Council. *Embracing Sustainable Consumption for a Happy Life—A Tracking Study on Consumer Behaviour*; Consumer Council: Hong Kong, China, 2021.
53. Calabrò, P.S.; Komilis, D. A standardized inspection methodology to evaluate municipal solid waste collection performance. *J. Environ. Manag.* **2019**, *246*, 184–191. [CrossRef]
54. Emmanouil, C.; Papadopoulou, K.; Papamichael, I.; Zorpas, A.A. Pay-as-You-Throw (PAYT) for Municipal Solid Waste Management in Greece: On Public Opinion and Acceptance. *Sustainability* **2022**, *14*, 15429. [CrossRef]
55. SQLI. *New Technologies Help Raise Chinese Citizens' Awareness of Waste Sorting*; SQLI: Lyon, France, 2020.
56. Moving Environment. Let's learn how to separate waste through a virtual reality game. Available online: https://movingenvironment.education/separate-waste-through-a-virtual-reality-game (accessed on 28 November 2022).
57. Cudjoe, D.; Yuan, Q.; Han, M.S. An assessment of the influence of awareness of benefits and perceived difficulties on waste sorting intention in Beijing. *J. Clean. Prod.* **2020**, *272*, 123084. [CrossRef]