Journal of Environmental Management 341 (2023) 118072

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Exploring greenhouse gas emissions pathways and stakeholder perspectives: In search of circular economy policy innovation for waste paper management and carbon neutrality in Hong Kong

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ARTICLE INFO

Keywords:
GHG emissions
Waste paper recycling
Circular economy
Shared socio-economic pathways
Hong Kong
Carbon neutrality

ABSTRACT

Waste paper disposed in landfills notably contributes to greenhouse gas (GHG) emissions and impedes more sustainable, circular alternatives, such as recycling. In Hong Kong, this unsustainable approach is currently dominant as 68% of waste paper products are treated in landfills in 2020. To contextualize the impact of local waste paper management and explore mitigation potentials of circular alternatives, this paper develops a quantitative assessment framework around GHG emissions development trajectories. Combining guidelines of the Intergovernmental Panel on Climate Change (IPCC), national GHG inventories, and local parameters from life cycle analysis, five GHG emissions projections were simulated along the Shared Socioeconomic Pathways (SSPs) until 2060. Most recent baselines indicate that Hong Kong's current waste paper treatment generated 638,360 tons CO_2-eq in 2020, comprising 1,821,040 tons CO_2-eq from landfill and 671,320 tons CO_2-eq from recycling, and −1,854,000 tons CO_2-eq from primary material replacement. Proceeding along a Business-as-Usual scenario under SSP5, GHG emissions will dramatically increase to a net 1,072,270 tons CO_2-eq by 2060, whereas a recycling-intensive scenario will lead to a net saving of −4,323,190 tons CO_2-eq. To complement the quantitative evidence on the benefits of waste paper recycling, field research was conducted to explore the feasibility of circular policy innovation from the perspective of recycling stakeholders. These empirical qualitative and quantitative findings from stakeholders' business routines and material transactions provide crucial indications for policy and institutional innovation: Essentially, for Hong Kong to improve waste paper recycling capacities and facilitate a circular economy (CE), local stakeholders require support via fiscal policy measures (financial subsidies or tax reductions) and infrastructure improvements (delivery access and material storage). In sum, this study employs a novel analytical framework combining original qualitative and quantitative evidence to provide policy innovation towards circular, GHG emission-saving waste paper management.

1. Introduction

Due to the widespread use of paper products in modern societies (Van Ewijk et al., 2021; Liang et al., 2012; Xu et al., 2021), 341.7 million tons ended up in global municipal solid waste (MSW) constituting about 17% of overall generated amounts in 2016 (World Bank, 2018). Likewise in Hong Kong, waste paper generation amounted to 1.7 million tons in 2020, making it (24%) the second largest constituent of MSW after food waste (30%) (HKEPD, 2021a). Currently, most MSW in Hong Kong is disposed of in sanitary landfills, while only a fraction is collected for recycling (Iqbal et al., 2019). In 2020, 68% (2668 t/d) of the city's waste paper was sent to landfills, while only 32% was recycled (HKEPD, 2021a). This recycling figure ranks substantially lower than comparable data for Europe (73.9% in 2020) or Japan (81.1% in 2021) (EPRC, 2021; PRPC, 2022). Beyond the material aspect, waste is a notable contributor to greenhouse gas (GHG) emissions. The waste sector accounted for around 3% of global GHG emissions in 2008 (Bogner et al., 2008) and increased to approximately 5% in 2016 (World Bank, 2018). In Hong Kong, where waste is the third largest source of GHG emissions after energy and transportation (HKEPD, 2021b), the emissions output increased from 3.4% in 2010 to 7.3% by 2019 (HKEPD, 2021b). In part, this deteriorating trend can be attributed to a decrease in MSW recycling. To counter these impacts, the Hong Kong Environmental Protection Department (HKEPD) has set targets to reduce MSW landfilling to

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https://doi.org/10.1016/j.jenvman.2023.118072
Received 7 December 2022; Received in revised form 20 April 2023; Accepted 28 April 2023
Available online 11 May 2023

45% and 100% in 2025 and 2035, respectively, and shift to alternative treatment options (HKEPD, 2021c).

Recycling as one such alternative ranks high in the priority strategies of the waste management (WM) hierarchy, which has been stipulated as a guiding principle by the European Union (EU) (Bertanza et al., 2021; DEFRA, 2011; EU, 2008; Ellen MacArthur Foundation, 2021; Pires and Martinho, 2019). Research has shown that waste recycling entails substantial net GHG emissions savings (Ayodele et al., 2018; Björklund and Finnveden, 2005; Cudjoe et al., 2021), which in turn renders recycling strategies are indispensable to achieve carbon neutrality targets (Ayodele et al., 2018; King and Gutberlet, 2013; Yang et al., 2020). Europe has for this purpose put efforts into exploring synergies between the circular economy (CE) and GHG emissions mitigation. The European Commission has along these lines stipulated more ambitious targets for MSW recycling with the overall benchmark to reach 65% by 2035 (European Environment Agency, 2021; Tisserant et al., 2017) and waste paper recycling to be raised to 85% by 2030 (European Commission, 2018). Such efforts are not only in line with the CE, but moreover facilitate achieving the United Nations' Sustainable Development Goals 11 (sustainable cities and communities), 12 (sustainable consumption and production), and 13 (climate action) (Sharma et al., 2021).

In Hong Kong, efforts to increase the waste paper recycling rate have been piecemeal, tacit and not substantially coordinated. From 1998 onwards, the Hong Kong Special Administrative Region (HKSAR) government established the set-up of three colored waste separation bins in residential sites to encourage households to participate in waste sorting and recycling (HKGOV, 2022; Lo and Liu, 2018). However, the waste paper recycling rate has continued to decrease in recent years due to the low participation of households in waste separation. The "Waste Paper Collection and Recycling Service Incentive Scheme" was launched to encourage recycling stakeholders to collect waste paper by providing economic incentives in 2020 (HKEPD, 2020). In August 2021, the Legislative Council passed the MSW Charging bill, which incentivizes proper segregation of waste and in turn its reduction at the household level. However, the scheme's implementation was delayed until 2023 (HKEPD, 2022) and paper separation and collection still largely relying on the formal-informal recycling system that centers on small preprocessors and frontline collectors.

The main motivation for this article is twofold. First, it aims at assessing the extent of GHG emissions from current waste paper treatment in Hong Kong and the future emissions mitigation potentials through recycling. The analytical framework adopts a life cycle perspective to contrast GHG emissions from both treatment methods. To further explore the potential dimensions of impacts from both treatment strategies, we further develop estimations along five Shared Socioeconomic Pathway (SSPs) scenarios. In doing so we provide a wider angle of GHG emission projections that both treatment approaches for waste paper will have under different future development contexts. Second, as impact quantifications are merely one factor influencing policy innovations, we buttress these findings with empirical evidence from interviews with local recycling stakeholders. This aspect provides a more holistic view of the local waste paper recycling sector and helps assessing stakeholder preferences for policy changes. The reason for this combined approach is the underlying conceptualization that regulations only perform effectively, if these achieve quantitative improvements and simultaneously serve stakeholder preferences (Steuer, 2020). Including the perspectives of directly involved stakeholders strengthen quantitative findings based arguments for policy innovation.

The novelty and relevance of this work are that it constitutes the first research attempt to analyze carbon neutral pathways of the waste paper sector in Hong Kong as it models the long-term dynamics of GHG emissions via the SSPs framework. While this work might provide the basis for WM and CE research in other sectors, the paper also aims at facilitating policy decisions. GHG emissions mitigation, the CE and carbon neutrality are critical environmental governance aspects for Hong Kong as aims at an overall GHG emissions reduction of 50% by 2035 as compared to 2005 (HKGOV, 2021).

The remainder of the paper is structured along the following sections: We first discuss relevant findings from earlier literature and then outline the methodological approaches of the study with a particular focus on the modeling of GHG emissions scenarios from waste paper treatment in Hong Kong. There, we assess GHG emissions quantification guidelines from the Intergovernmental Panel on Climate Change (IPCC), national GHG inventories, and first-hand data from field research. The quantitative results section outlines current and future levels of waste paper generation and GHG emissions pathways up to 2060 for the five Shared Socioeconomic Pathways (SSPs) scenarios. The qualitative results section presents empirical qualitative evidence from the field and discusses implications for policy innovation towards more circular treatment approaches that contribute to carbon neutrality and GHG emission goals of Hong Kong.

2. Literature review

2.1. Circular economy and carbon neutrality

Previous research has shown that the CE constitutes an impactful strategy to respond to the global climate change challenge (Ellen MacArthur Foundation, 2019). A total of 45% of the current global GHG emissions, stemming from the production of food, steel, cement, plastic, and metals, can be prevented via the implementation of CE strategies. These center on the application of R-principles (e.g. refuse, reduce, reuse, remanufacture, and recycle) in production and consumption so as to maximize resource-efficient use that reduces environmental impacts (Potting et al., 2017; Ellen MacArthur Foundation, 2021). Previous studies have identified the benefits of recycling as a CE strategy for reducing carbon impacts (Andreoni et al., 2015; Clarke et al., 2019), e.g. for food waste in Sweden (Eriksson et al., 2015) or Australia (Edwards et al., 2017), and waste paper in Denmark (Schmidt et al., 2007). For China's plastics waste, recycling was found to lower GHG emissions compared to traditional landfilling by 7.67 and 14.57 million tons in 2007 and 2016, respectively (Liu et al., 2018). Likewise, a recycling scenario for e-waste in China featured a total GHG emissions reduction potential of 390 million tons for the period 2013–2017 (Yang et al., 2020).

2.2. GHG emissions of the MSW sector

MSW management has been identified as one of the largest GHG emissions sectors (Bian et al., 2022). Thus, several studies have reported GHG emissions from MSW and compared alternative waste treatment strategies at the national, regional, provincial, and city levels (Banar et al., 2009; Dastjerdi et al., 2021; De Feo and Malvano, 2009; Kang et al., 2022; Mühle et al., 2010; Vergara et al., 2011; Zhao et al., 2009). The GHG emissions from MSW management in Nottingham, England were assessed from 2001 to 2017 by life cycle assessment (LCA) (Wang et al., 2020). In China, incineration was found to achieve substantial decreases in GHG emissions compared to landfill, composting, and anaerobic digestion, having the highest rate for energy recovery and grid emissions substitution (Liu et al., 2017). Studies have also explored recycling strategies for GHG emissions mitigation from MSW in general (Clarke et al., 2019; Dong et al., 2018; Gadaleta et al., 2022), with attention to specific recyclables like plastics (Liu et al., 2018) and Waste Electrical and Electronic Equipment (Yang et al., 2020) among others. Research on GHG emission saving potentials by sustainable MSW treatment is so far lacking for Hong Kong, including the stream of waste paper.

Most related research that assesses current total GHG emissions from the WM sector revolves around alternative disposal scenarios. Few of these studies provide accurate future GHG emission pathways for the MSW sector, nor do these consider the potential of CE approaches. The benefit of GHG emission pathways is to quantitively demonstrate the potential for future WM regimes. Picking up on this shortcoming, our assessment looks at the correlation with socioeconomic factors like gross domestic product (GDP), as well as population growth and density (Beigl et al., 2008; Izquierdo-horna et al., 2022; Wu et al., 2020). Additionally we account for the SSPs framework, which is considered a useful tool to analyze potential socioeconomic trajectories of climate change (Dellink et al., 2017; Neill et al., 2017; Riahi et al., 2017).

3. Methods and materials

3.1. Field research in Hong Kong

Hong Kong is one of the most densely populated places in the world, with an area of just 1104 km^2 and over 7.4 million residents (Census and Statistics Department Hong Kong, 2021). The city generates large quantities of waste paper on a daily basis (4657.53 tons/day in 2020) (HKEPD, 2021a) and is taken as case study in this article. Waste paper mainly originates from households and public areas, including residential buildings, litter bins, streets, and parks. A sub-stream of commercial and industrial waste paper is generated by shops, restaurants, hotels, offices, markets in private housing estates, and industrial areas (HKEPD, 2019). The main types of waste paper recorded in Hong Kong are cardboard, newsprint, office paper, paper-based beverage containers, and other paper-based products (like paper tissues, paper bags, paper dining ware, etc.) (HKEPD, 2021a).

The key stakeholders in the city's half-formal, half-informal recycling system are frontline collectors, small preprocessors and exporters. To firstly ascertain stakeholder networks and inherent recyclable material flows, field research activities including interviews and observations were conducted between September and November 2021 (see Supporting information Annex). For the waste paper preprocessors, the interviews covered (a) all relevant operational modes, i.e. stationary recycling corner shops as well as mobile and semi-stationary pop-up recyclers; (b) a range of representative locations with different population densities; and (c) stakeholders with small, medium and large daily processing volumes. The specifics of the sample group are summarized in Table 1. For the frontline collectors, 28 individuals were interviewed directly after they had sold collected waste paper to preprocessors. Inquiries focused specifically on operational routines (collection distances, motivation, transport patterns, etc.) and daily collected quantities. These amounts were double-checked against the recordings of actual quantitative transactions that recycling stations collect on a per person basis. Finally, two expert interviews were conducted: First, with an exporter of waste paper in Sheung Shui area to gather information on export quantities, export procedures, export routes, material transportation and cooperation with downstream recycling paper mills. Second, an expert on waste paper in the city's Environmental Protection Department was interviewed regarding the number of stakeholders in the waste paper recycling industry.

Table 1
Field research on waste paper preprocessors in Hong Kong.

Date of interview	Location of preprocessor	Operational mode	Mean recovery volumes (t/day)
September 09, 2021	Kowloon City	Stationary recycling corner shops	8–9
September 13, 2021	Shui Bin Wai	Semi-stationary pop-up recyclers	10
September 16, 2021	Tin Shuiwai	Semi-stationary pop-up recyclers	0.5
September 17, 2021	Kennedy Town	Stationary recycling corner shops	1
September 15, 2021	Sha Tin Market	Semi-stationary pop-up recyclers	32
September 17, 2021	Hung Fuk Court	Mobile pop-up recyclers	0.15
September 18, 2021	Lok Fu	Mobile pop-up recyclers	1–1.3

3.2. GHG emissions of waste paper treatment in Hong Kong

3.2.1. Goal and scope of the study

This section assesses the environmental impact of GHG emissions from waste paper treatment in Hong Kong to develop a baseline, business-as-usual GHG emissions scenario. Waste paper from households and commerce is either transferred to sanitary landfills for final disposal or syphoned into local recycling. To specify the analytical scope, Fig. 1 outlines the system boundaries, which are organized as:

(1) Waste paper recycling process
(2) Waste paper landfilling process
(3) Replacement of virgin paper using recycled waste paper
(4) Transportation processes:
- Transportation from preprocessors to exporters
- Transportation from exporters to recycling mills
- Transportation from refuse transfer stations to landfill sites

The net amount of GHG emissions generated by recycling can be calculated on the basis of Ayodele et al. (2018) and Cudjoe et al. (2021) as:

$$GHG_{net\ recycling} = GHG_{recycling} - GHG_{Replacement\ of\ virgin\ paper\ (avoided)} + GHG_{recycling\ transportation} \tag{1}$$

The net amount of GHG emissions from landfill is thus:

$$GHG_{net\ landfill} = GHG_{landfill} + GHG_{landfill\ transportation} \tag{2}$$

The total amount of GHG emissions from recycling and landfill again is:

$$GHG_{total} = GHG_{net\ recycling} + GHG_{net\ landfill} \tag{3}$$

where $GHG_{net\ recycling}$ denotes the net GHG emissions from waste paper recycling, $GHG_{recycling}$ represents GHG emissions occurring from recycling waste paper into secondary paper, $GHG_{Replacement\ of\ virgin\ paper\ (avoided)}$ stands for GHG emissions from paper production using virgin material, and $GHG_{recycling\ transportation}$ captures GHG emissions from transportation during recycling processes, $GHG_{net\ landfill}$ describes net GHG emissions from landfilling, $GHG_{landfill}$ are emissions resulting from landfilling, $GHG_{landfill\ transportation}$ are GHG emissions emerging form transportation to landfills, GHG_{total} denotes the total GHG emissions from landfill and recycling processes. The period of this study covers 2017 to 2020 as transportation modes for waste paper had changed substantially in 2017 (see section 3.2.3).

3.2.2. Assessing GHG emissions arising from waste paper treatment

3.2.2.1. GHG emissions from landfilling waste paper. GHG emissions from landfilling can be assessed on the basis of the "2006 IPCC Guidelines for National GHG Inventories" (IPCC 2006 Guidelines hereafter) (IPCC et al., 2006), the "2019 IPCC Guidelines for National GHG Inventories" (IPCC 2019 Guidelines hereafter) (IPCC et al., 2019), and the "Guidelines for Preparing Provincial GHG Inventories (Trial Implementation) (2011)" (the Guidelines for China hereafter) from the National Development and Reform Commission of China (NDRC) (NDRC, 2011). The majority of GHG emissions released during landfill takes the form of methane (CH_4) that results from the decomposition of the organic carbon content in waste paper (IPCC et al., 2006). To enhance the accuracy of calculations, local emission factors were collected from secondary literature and fieldwork. Biogenic CO_2 emissions and N_2O emissions were not taken into account in this study as biogenic CO_2 emissions are considered relevant only in Agriculture, Forestry and Other Land Use (AFOLU) sectors, while N_2O emissions are not

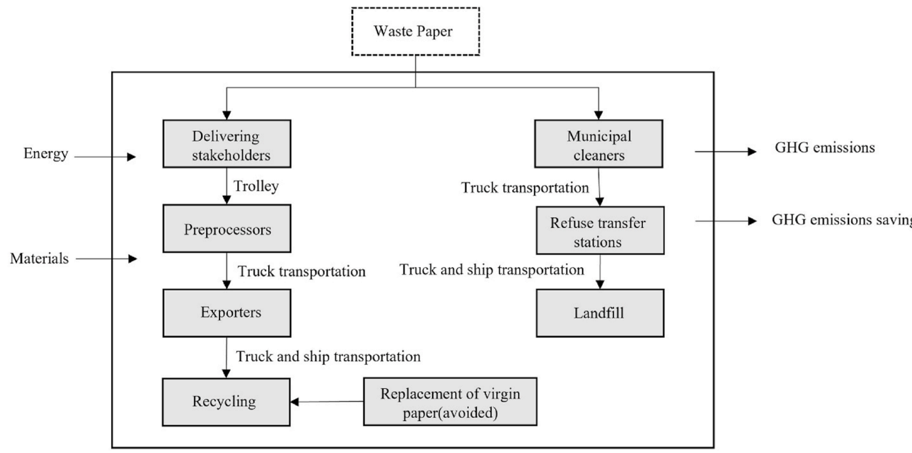


Fig. 1. The system boundaries of waste paper treatment in Hong Kong.

significant for the waste paper stream (IPCC et al., 2006).

The CH_4 emissions from landfill disposal are calculated as:

$$CH_{4_{Landfill}} = \left[\sum CH_{4_{generated}} - R\right] \times (1 - OX) \tag{4}$$

where $CH_{4_{Landfill}}$ is the net CH_4 of waste paper disposed in landfills (in thousand tons); $\sum CH_{4_{generated}}$ is the total amount of CH_4 generated from waste paper disposal (in thousand tons); R is the recovered CH_4 (in thousand tons) at the landfill site; and OX is the oxidation factor (%). $\sum CH_{4_{generated}}$ can be calculated as

$$\sum CH_{4_{generated}} = \sum\left(W \times DOC \times DOC_f \times MCF \times F \times \frac{16}{12}\right) \tag{5}$$

where W denotes the mass of waste paper disposed (in thousand tons); DOC is the degradable organic carbon of waste paper (kg C/kg); and DOC_f is the waste paper fraction of DOC that can decompose; MCF is the CH_4 correction factor for aerobic decomposition; F is the proportion of CH_4 in landfill gas (in %); and 16/12 is the molecular weight ratio of CH_4/C.

The DOC reference values of typical waste paper components used in this article are listed in Table 2. In Hong Kong, F is taken as 50% (Dong et al., 2017; NDRC, 2011; Woon and Lo, 2013), R is 40% of $\sum CH_{4_{generated}}$ emissions (Dong et al., 2017), and the constant value of OX is 10% (NDRC, 2011; Woon and Lo, 2013). Landfill management in Hong Kong adheres to "deep and managed" practices (HKEPD, 2021d); therefore, MCF is recommended to be 1 by IPCC et al., 2006 and 2019 (IPCC et al., 2006; NDRC, 2011; Woon and Lo, 2013), and DOC_f is 0.5 as per recommendation of IPCC et al., 2019 due to the waste stream consisting of moderately decomposable recyclables e.g., paper, textiles (IPCC et al., 2019).

3.2.2.2. GHG emissions from waste paper transport to landfills. In Hong Kong, MSW is generally collected from households, companies or commercial entities, delivered to refuse transfer stations (RTSs) and finally transported onward to strategic landfills (HKEPD, 2021a). To simplify estimations on transportation distance, only the transportation from RTSs to landfills is considered. The transportation distances between seven RTSs to two landfill sites are estimated on the basis of weighted arithmetic mean distances (Table S1). The transportation from the five RTSs to the WENT (West New Territories) Landfill site is by sea, namely, from IETS (Island East Transfer Station), IWTS (Island West Transfer Station), OITF (Outlying Islands Transfer Facilities), NLTS (North Lantau Transfer Station), and WKTS (West Kowloon Transfer Station) (HKEPD, 2021a). The average shipping distance is approximately 70 km (round trip) and is assumed to include one trip per day from each RTS to WENT (Woon and Lo, 2013). The average transportation distances from NWNTTS (North West New Territories Transfer Station) to WENT and from STTS (Shatin Transfer Station) to the North East New Territories (NENT) Landfill are assumed to be 40 km and 60 km per round trip, respectively, based on the Google Maps geographic tool. The capacities of the refuse collection vehicles are below 16 tons, between 16 and 24 tons, and above 24 tons (HKEPD, 2015). For emissions arising from ship and truck transport, data was sourced from the Ecoinvent 3.5 database (Ecoinvent Centre, 2018).

Table 2
The DOC characterization of waste paper in Hong Kong (Dong et al., 2017; IPCC et al., 2006; Iqbal et al., 2019; Woon and Lo, 2013).

MSW component	Dry matter content in % of wet weight	DOC content in % of wet waste	DOC content in % of dry waste	Total carbon Content in % of dry weight
Paper/ cardboard	72.3	36.5	50.5	41.9

3.2.3. GHG emissions from waste paper recycling

In 2020, 98.2% of waste paper was sent aboard for recycling, and only approximately 1.8% was recycled locally as Hong Kong lacks the required processing facilities (SCMP, 2017). Most waste paper collected in Hong Kong is exported to paper mills in Guangdong province, mainland China, with small quantities being sent to other Southeast Asian countries (Comtrade U.N., 2021). From the data of all paper recycling mills in Guangdong obtained by the authors, it is safe to assume that all exported waste paper was finally transported to Guangzhou and Guangdong paper recycling mills. The GHG emissions from waste paper recycling arise from four processes: waste paper collection, transportation, (chemical) reprocessing and pulp- and papermaking (Man et al., 2019; Zhang et al., 2021). It is estimated that 1 ton of waste paper can produce 0.8 tons of pulp to serve as feedstock for production of new paper products (Liu et al., 2020).

In the waste paper collection market, the means of transportation are trucks and container ships. The capacities of trucks owned by preprocessors were assessed during fieldwork (Table S2). The average transportation distances of waste paper recycling processes are shown in Table S3 and Table S4. Both truck and container ship emission figures (Table S4) are based on the Ecoinvent 3.5 inventory (Ecoinvent Centre, 2018).

The secondary recycled materials produced by the recycling process can replace the production of corresponding primary materials (virgin raw materials), which saves energy, raw materials and emissions (Pérez et al., 2018). The GHG emissions from using virgin fiber material to manufacture new paper products originate from the processes of raw material cultivation and harvest, collection and transportation, pulping and use of chemicals, and papermaking (Man et al., 2020). The GHG emissions from waste paper recycling and new paper production from virgin materials are shown in Table 3.

3.2.4. Uncertainty analysis

In this study, the uncertainty analysis for GHG emissions from waste paper treatment was conducted by using the Monte Carlo simulation. The technique generates 10,000 iterations to estimate possible outcomes of an uncertain event, which in turn provides mean and standard deviation. For the present study, the software kit R was used to perform the simulation.

3.3. Dual scenario prediction of GHG emissions from waste paper treatment until 2060

Modeling GHG emissions for future scenarios used predictions on future waste paper generation. Ordinary least squares (OLS) regression analysis was used in this study. Waste paper generation per capita is the dependent variable and population and GDP per capita represent the independent variables. The regression was performed with the following specifications:

$$WP_i = \beta_0 + \beta_1 POP_i + \beta_2 GDP\ per\ capita_i \tag{6}$$

where i refers to the year, WP_i to annual waste paper generation per capita (kg/cap/yr), POP_i to population (in million), and $GDP\ per\ capita_i$ referring to GDP divided by its total population (in 2005$PPP). A regression analysis was conducted to investigate the relationship between waste paper generation per capita and population, and GDP per capita during the period 2000 to 2020. The data for waste paper generation from 2000 to 2020 was taken from Hong Kong's waste statistics (HKEPD, 2021a). The historical GDP data in the unit of 2005$PPP and the historical population from 2000 to 2020 were obtained from Koch and Leimbach, 2023). To test the robustness and reliability of the regression model, the MAPE (mean absolute percentage error) values were calculated (Hyndman and Koehler, 2006; Kannangara et al., 2018). MAPE is defined as follows:

$$MAPE = \frac{100}{n}\sum_{t=1}^{n}\left|\frac{Y_t - \widehat{Y}_t}{Y_t}\right| \tag{7}$$

where n is the number of observations, $\widehat{Y_t}$ is the value predicted by the model, and Y_t is the observed value.

Considering the impact of the Covid-19 pandemic's shock on future GDP and population, this study adopted the updated SSPs GDP and population scenarios from 2020 to 2060, as model inputs for each SSPs scenario (Koch and Leimbach, 2023). GDP and population projection trends are given for 5-year intervals and were interpolated into annual data points in this study. According to Hong Kong's zero waste target in the "Waste Blueprint for Hong Kong 2035", the recovery rate of MSW is set to increase to 55% by 2025 and 100% by 2035 (HKEPD, 2021c). These are very high benchmarks set by the government, especially in light of past shortcomings in MSW reduction (Lee, 2020). Yet for exploring the best possible GHG emissions reduction range achieved via recycling, the simulation assumes that the waste paper recycling rate will be 55% by 2025 and 100% by 2035 in this study. To subsequently analyze the GHG emissions of future waste paper treatment pathways, two scenarios were selected: A business as usual (BAU) scenario assuming the future recycling rate to stay constant from 2020 onwards and a Strong Recycling (SR) scenario that projects recycling to increase to 55% in 2025 and 100% by 2035. Given the complexity arising from projecting GHG emissions along five different SSPs, we decided to contrast a worst (BAU) with a best possible (SR) scenario to simulate the potential range of GHG emissions from future waste paper recycling.

Table 3
The in average GHG emissions from waste paper recycling and paper production using virgin materials in the Chinese papermaking industry (based on Man et al., 2020).

Waste paper recycling for paper production	GHG emissions (tCO_2-eq/t waste paper)	Paper production using virgin materials	GHG emissions (tCO_2-eq/t paper)
Collection and transportation	0.01*	Raw material cultivation, harvest and collection	0.045
		Transportation	0.21
Chemicals and pulping	0.43	Chemicals and pulping	3.475
Papermaking	1.42	Papermaking	1.42

(*) Estimations by the authors, based on Ecoinvent 3.5 and empirical field research findings.

4. Quantitative results

4.1. The network structure of waste paper recycling

The field investigation conducted by the authors revealed that at the center of Hong Kong's recycling system stands a formal-informal symbiotic network, which has been in place for decades. Its main stakeholders that also dominate waste paper recycling are 1) frontline collectors (non-registered, individual waste collectors and cleaners of residential buildings), 2) preprocessors, and 3) exporters. Current estimations outline approximately 4000 frontline collectors, 300 waste paper preprocessors and 16 paper scrap exporters in Hong Kong in 2021 (HKEPD, 2021e, personal communication with an expert of the Environmental Protection Department, October 18, 2021). Particularly frontline collectors and preprocessors initially operated informally, while some gradually registered with the government over the past years. Furthermore, to consolidate the collection and recycling of waste materials, the government not only issued sanitation and security regulations, but also provided incentive schemes "The "Waste Paper Collection and Recycling Service Incentive Scheme" to both stakeholder groups (HKEPD, 2020). This latter measure helped mitigating labor fluctuations among collectors, reduced potential feedstock supply risks and thus safeguarded the steady flow of waste paper to preprocessors. Although more formal collection points, i.e., *Green@Community* recycling stations, are promoted by the government since 2015 (HKEPD, 2021c), most of the waste paper is still collected by frontline collectors (personal communication with an expert of the Environmental Protection Department, October 18, 2021). Given this systemic feature, the study focuses on the waste paper material flow provided by frontline collectors.

In the formal-informal symbiotic network, frontline collectors search for and collect waste paper from streets, playgrounds, markets, commercial shops, and waste bins within residential buildings, and they transport the materials with trolleys (Chua, 2016). These trolleys are the stakeholders' main tools for waste paper collection and transportation because trolleys are often the best choice for short-distance loading and unloading of goods in high-density buildings and narrow roads in Hong Kong (Lo and Liu, 2018). After several stops to gather and on-load materials, the collectors push full trolleys to recycling shops on foot within a mean distance of 1 km (estimated by the authors during the field research). Preprocessors, stationary recycling corner shops as well as mobile, semi-stationary pop-up recyclers, are usually located near residential areas or on commercial streets. They receive, sort and bale waste paper from generators and frontline collectors. The so-prepared waste paper is then uploaded to trucks and transported to exporters (Fig. S1). Exporting enterprises then first sort waste paper into sub-categories (cardboard, newsprint etc.), and thereupon shred, re-bale, store, and finally transport it to the Tuen Mun river trade terminal. Previously, waste paper was exported to Guangdong paper mills via inland barge transportation but since China's import restrictions starting in 2017 waste paper has mostly been loaded into containers and transported by container ships to other destinations (personal communication with Mr. Lau, a waste paper exporter in Sheung Shui, November 11, 2021).

Frontline collectors, preprocessors and exporters are the essential nodes in Hong Kong's waste paper collection network (Fig. 2). Preprocessors are situated in all 18 districts according to the Hong Kong Collector & Recycler Directory (HKEPD, 2021f). Most have set up shops in Yuen Long (18.3%), Kwun Tong (12.9%), and the Northern Territories (10.8%) (Table S5). In total, 25.5% operate as multi-recyclable collection points, recovering waste paper, plastic waste, electronic devices, ferrous metals, and non-ferrous metals from frontline collectors (Table S5). A set of contractors of collection and recycling points for the waste paper were appointed by the EPD in July 2020 and act as registered exporters of waste paper to mainland China's paper mills (HKEPD, 2021e).

4.2. GHG emissions from waste paper treatment in Hong Kong in 2017–2020

The amount of GHG emissions generated by waste paper treatment from 2017 to 2020 is shown in Fig. 3. In 2017, landfilling waste paper generated 1,744,560 tons of CO_2-eq. In addition, 1,182,260 tons of CO_2-eq GHG emissions were generated during the waste paper recycling process, and the avoided GHG emissions from paper production from primary materials were −3,265,100 tons of CO_2-eq. Therefore, the net GHG emissions from waste paper treatment were −338,280 tons of CO_2-eq in 2017. This net GHG emissions value indicates that waste paper recycling has the potential to achieve substantial emissions mitigation. The net GHG emissions in 2020 dramatically increased to 638,360 tons of CO_2-eq in 2020 owing to the decreased recycling ratio. The decreasing recycling rate resulted in higher GHG emissions from landfill, explaining why net GHG emissions were negative in 2017, but positive in 2018–2020 (see Fig. 3).

4.3. Uncertainty analysis

The values of eight sensitive parameters are summarized in Table S6. With 10,000 Monte Carlo sampling iterations, the distribution of the net GHG emissions from the waste paper treatment sector in 2017 is shown in Fig. 4. The GHG emissions vary from −840,160 tons of CO_2-eq to −1,956,830 tons of CO_2-eq, with a mean of −1,447,400 tons of CO2-eq and a standard deviation of 147,200 tons of CO_2-eq at a 95% confidence level. The resulting uncertainty factor driven by the parameter variation shows that the study's calculation is robust.

4.4. Future pathway of GHG emissions from waste paper treatment

The results of the OLS regression are shown in Table 4. The R-squared value of this regression is 0.85, which indicates that the regression line fits the data reasonably well. The evaluation results of MAPE are classified into four types: excellent (MAPE <10), good (MAPE = 10), acceptable (MAPE = 20–50), and unacceptable (MAPE >50) (Lewis, 1982). The MAPE value is 3.1% (Table S7), which indicates an excellent prediction outcome. The GDP per capita also has a significant positive effect on the waste paper generation per capita at a 1%

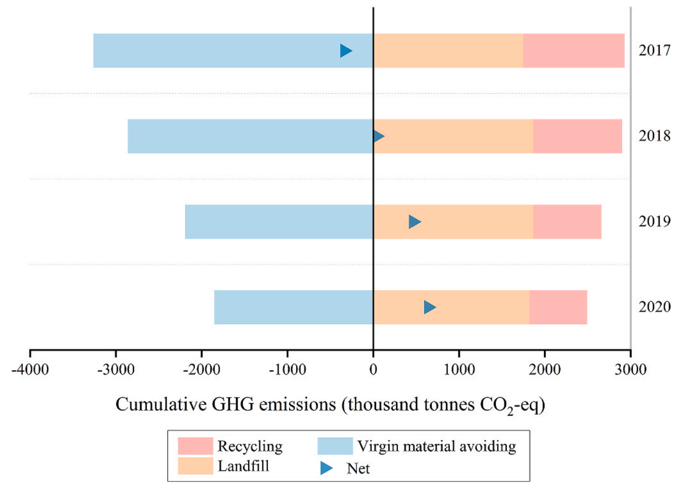


Fig. 3. GHG emissions from the waste paper treatment in Hong Kong from 2017 to 2020.

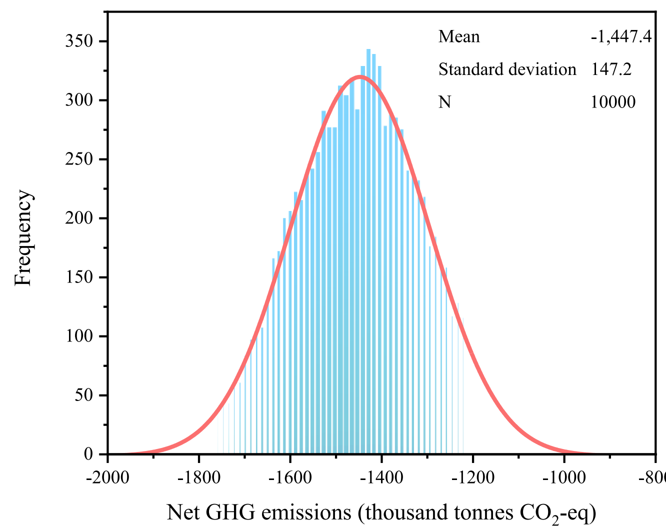


Fig. 4. Distribution of the GHG emissions (thousand tons CO_2-eq) in 2017 after the Monte Carlo simulation.

significance level.

It is estimated that, up to 2060, waste paper generation per capita will vary between 162 and 595 kg/cap/yr., and overall waste paper generation will be within 1.46 and 4.03 million tons under the five SSPs. The GHG emissions pathway of the two scenarios is presented in Fig. 5. Under the BAU scenario, Hong Kong's society will still face climate change challenges with GHG emissions of 2,623,640 tons of CO_2-eq in SSP3 and at least 1,072,270 tons of CO_2-eq in SSP5 in 2060. However, under the SR scenario, waste paper management shows a vast potential for GHG emission mitigation. In the SSP5 scenario, given that the

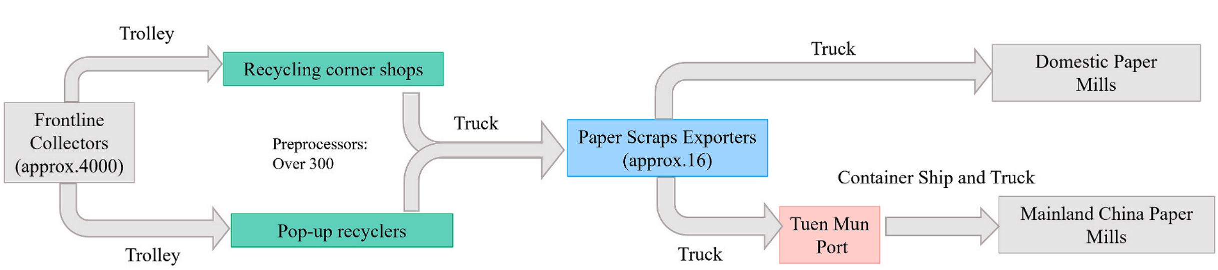
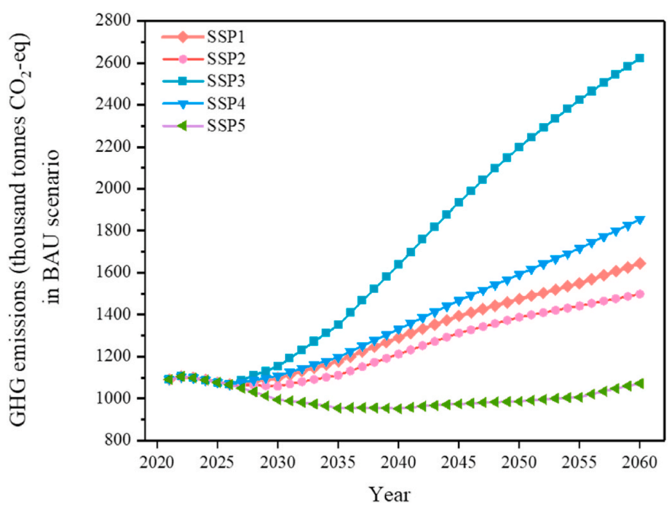


Fig. 2. The waste paper recycling network in Hong Kong as of 2021 (Source: HKEPD, 2021f; HKEPD, 2021g, by author).

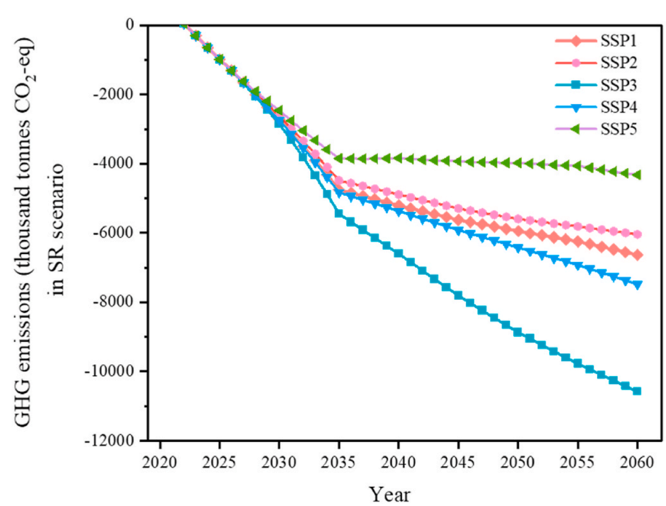
Table 4
The regression result of waste paper generation per capita.

	Coefficients
POP	−244.88*** (5.0E-08)
GDP per capita	0.00719*** (1.87E-06)
Intercept	1662.52*** (2.12E-09)
Observations	21
R Square	0.85
Adjusted R Square	0.84
F statistic	51.660*** (3.48E-08)

Note: *p < 0.1; **p < 0.05; ***p < 0.01.



(a)



(b)

Fig. 5. The GHG emissions for waste paper treatment under five SSPs up to 2060 for (a) BAU scenario and (b) SR scenario.

recycling rate reaches 55% in 2025 and 100% in 2035, GHG emissions could be reduced to −985,150 tons of CO_2-eq and −3,847,300 tons CO_2-eq in 2025 and 2035 respectively. And it is estimated that this figure will be −4,323,190 tons in 2060. The results for the two scenarios show that whether GHG emissions from waste paper treatment will increase or decrease is essentially determined by MSW recycling rates. This interdependency and the varying probability of the SSPs to emerge underscores the need for future GHG emissions forecasting to identify maximum GHG emission reductions potentials and in further consequence use these as basis for policy innovation.

5. Qualitative results and implications for policy innovation

The quantitative assessment of waste paper treatment in Hong Kong highlights the enormous amount of GHG emissions generated between 2017 and 2020. For a more carbon neutral and CE future, the simulation of the SR scenario indicates the tremendous potential waste paper recycling offers for Hong Kong. Historically, waste paper recycling in Hong Kong has relied on the cooperation between frontline collectors, preprocessors, and exporters. The first two of these stakeholder groups are individually small in scale and work within legal grey zones and few formal institutional safeguards. Given this relatively volatile context maintaining a smooth, durable recycling network that operates at low transaction cost levels is critical (Liu et al., 2020; Steuer et al., 2018). As of now, the formal-informal symbiotic network around waste paper transactions has proven effective within certain boundaries. On the one hand, our qualitative interview findings confirmed that collectors and preprocessors are both highly satisfied with the opposite group's operational routines and business patterns (pricing, negotiation, information sharing). This in turn induced frontline collectors to exchange materials relatively frequently, i.e. twice a day. Moreover, interviews with one preprocessor indicated that gross turnover from waste paper was HK $1300 HKD/ton in September 2021, which he explained as providing sufficient revenue to continue businesses operations (personal communication with preprocessor, Kowloon City, September 9, 2021).

On the other hand, the system is vulnerable to external disruptions, e.g., when mainland China began to implement a series of waste import restrictions in 2017. These prevented unsorted waste paper transfers to mainland China, which led Hong Kong's waste paper recycling sector to faced significant headwinds. With the closure of the traditional export channel waste paper price-building became exclusively determined by Hong Kong's comparably weak paper market. The response of the Hong Kong government was to implement the "Waste Paper Collection and Recycling Service Incentive Scheme" in September 2020, which aimed at random waste paper dumping on the streets and helped reinvigorate collection. The scheme offers preprocessors & exporters HK$600/ton in subsidies (Chen, 2020), out of which frontline collectors are to be paid no less than HK$0.7/kg (HKEPD, 2020). This fiscal policy measure received immediate positive responses from recycling operators. One interviewed preprocessor further indicated the importance of the scheme for being able to continue in paper recycling (personal communication, preprocessor in Kowloon City, September 9, 2021). Such drastic statements are not uncommon among preprocessing stakeholders, who typically point out high daily expenditures, e.g. labor costs of HK$7000–15,000/cap/month and transport vehicle maintenance costs of HK$300–1000/day/vehicle, as major challenges (personal communication with several stakeholders, September 2021). The matter of costs as the most pressing issue for operators is indirectly corroborated by a Likert-scaled assessment of pre-selected challenges we inquired among preprocessing stakeholders during the interviews. Table 5 shows their responses, which clearly indicate that high taxation or a lack of subsidies was considered as most pressing, while constraints from surrounding infrastructure ranked second.

The evaluation of preprocessors provides valuable directions for policy-making on waste recycling. To some extent it appears that this bottom-up feedback was taken up by local legislators. In mid-2021, the Environmental Protection Department issued a purchasing policy obligating for exporters to pay not less than HK$0.75/kg to preprocessors (HKEPD, 2021g), which indicates the extension of the 2020 Waste Paper Collection and Recycling Service Incentive Scheme.

However, contrasting these qualitative findings with policy developments show some, in parts substantial shortcomings. First, surrounding infrastructure constraints, particularly in regard to space for

Table 5
Five-point Likert scale assessment of challenges for preprocessors in Hong Kong.

Location of preprocessor	Evaluated challenges					
	Business constraints from local regulations	High taxation/ insufficient subsidies	Transfer routines by upstream collectors	Recyclable storage options	Constraints from surrounding infrastructure	Competition from other preprocessors
Kowloon City	2	5	1	4	4	1
Shui Bin Wai	5	5	3	5	5	2
Tin Shuiwai	3	5	1	1	1	1
Kennedy Town	1	1	1	1	5	1
Sha Tin Market	1	5	5	4	4	1
Hung Fuk Court	4	4	3	2	3	1
Lok Fu	4	4	5	2	2	3
Mean value	2.9	4.1	2.7	2.7	3.4	1.4

off- and on-loading of materials for transport, access to roads, short-term parking and storage possibilities outside of preprocessing stations, are all aspects requiring additional policy attention. So far, however, industry efforts to lobby for regulatory changes have been to little avail (DWW, 2021). Second, the development of local waste paper processing structures is stagnating and, in part, even receding. The comparatively large-scale Nanhua paper mill, with a capacity of 260 tons/day, closed in 2006 (HK01, 2020), and was merely replaced by a pulp mill, Mil Mill that was set up in October 2019 (Mil Mill, 2021). Mil Mill exclusively focused on paper-based beverage containers and despite the facility's capacity of 60 tons/day, it is only supplied with 2–3 tons daily (SCMP, 2022a). To make matters worse, Mil Mill's operations seem to have come to an end by December 2022, as the facility's land lease from a public corporation will not be extended. In terms of explanation, commentators identified the public entity's perceived lack of Mil Mill's innovation capacity as the main reason for the cancellation of the rental agreement (SCMP, 2022b). The underlying problem in both cases is the general neglect of fostering local paper recycling structures. Paper (packaging) products are ubiquitous in the city, hence, developing capacities to reprocess paper discards into feedstock for production would constitute a first milestone towards a local CE for some paper produce. Economically, that strategy could reduce high transaction prices due to low external market dependency, while in terms of circularity, it could further foster more narrow loops between local demand and local industries. From a life-cycle perspective, local recycling, moreover, would in all likelihood lead to a substantial reduction in emissions. Local transportation implies lower distances than exports to neighboring mainland China, which could effectively decrease GHG emissions (Tomberlin et al., 2020).

Based on the results, the following policy innovations are suggested to promote carbon neutrality for Hong Kong's waste paper management. From the perspective of end-of-life treatment, our simulations show substantial emission reduction benefits, should waste paper treatment shift from landfilling to recycling. However, as the recycling system rests on volatile factors, an interest-inclusive formalization or integration of collecting stakeholders is key for achieving a sustainable waste recycling system. As evidenced by the effects of the subsidy scheme and stakeholder perspectives fiscal policy support (to bolster labor- and operational expenditures) and accommodating regulations for infrastructure management need to be provided by the government. In final instance, as a more general suggestion, there is need for further public awareness campaigns that aim at improving local residents' recyclable waste segregation, which could in turn facilitate recyclable collection efforts.

6. Conclusion

To achieve the city's carbon neutrality target, it is necessary for Hong Kong to pay attention to MSW treatment sectors sustainable transition. This paper quantitively assesses the GHG emissions from waste paper treatment in Hong Kong from a life cycle perspective, and conducts future predictions along the SSPs to assess GHG emissions saving potentials. The results present a novel finding on the comprehensive long-term pathway of waste paper treatment associated with the carbon emissions profile in Hong Kong. Field research was conducted to identify features and operative patterns of the waste paper recycling industry and localize the GHG emissions generated from waste paper treatment. The total GHG emissions of this sector were −338,280, 36,150, 463,560, and 638,360 tons of CO_2-eq over, 2017, 2018, 2019, and 2020, respectively. Two scenarios were developed under five SSPs until 2060. GHG emissions would be 1,072,270 tons of CO_2-eq in the BAU scenario, but only −4,323,190 tons in the SR scenario under SSP5 in 2060. These potential mitigation figures however only hold, if the government pushes policies for MSW recycling rates and essentially redesigns its sustainable MSW management system in line with local recyclers' interests. The quantitative evidence on the benefits of waste paper recycling are combined with qualitative insights provided by Hong Kong's recycling stakeholders so as to develop tailor-made suggestions for policy innovation. Formalizing the symbiotic formal-informal recycling system is central to maximizing potential capacities in waste paper collection and recycling. Critical in that regard is the need to support the effective upstream operations between collection and preprocessing, ideally via the implementation of fiscal support measures and extended permissions in the use of infrastructure for pre-processing facilities.

This study explores novel angles through quantitative assessments on current and future carbon neutral emission pathways of and qualitative verifications of recycling stakeholders in Hong Kong's waste paper treatment. In combining these findings, the paper provides support for political decision-making towards a sustainable WM system transition. As a concept, the methodology for long-term GHG emission simulations along the SSPs in waste recycling can serve as analytical blueprint for application to other regions and sectors.

In addition, there are aspects not covered in the present study which could be interesting for upcoming research. For example, the precise technical information on future waste paper treatment can be explored via prediction models along the GHG emissions pathways. Furthermore, in light of the high electricity consumption for pulping, the potential use of renewable energy for waste paper recycling constitutes an important, yet still unexplored field. In addition, as only the socioeconomic indicators of GDP and population were selected to predict future waste paper generation, further socioeconomic determinants like living standards, or industrial structure could be investigated. Finally, additional waste streams (like plastics, glass, and metals) in Hong Kong should be assessed along the SSPs framework to provide a holistic evaluation of GHG emissions from MSW management.

Credit author statement

Peixiu, CHEN: Conceptualization, methodology, field research, validation, formal analysis investigation, data curation, writing - original draft, review & editing, visualization, Meike SAUERWEIN: Methodology, formal analysis, writing - review & editing, Benjamin STEUER: Conceptualization, validation, writing – original draft, review & editing, supervision, project administration, funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data is provided in the main text or in the supplementary information section

Acknowledgments

This paper resulted from a research activity commissioned by the Neighbourhood Bottle Reward Scheme of Drink Without Waste and Designing Hong Kong. Funding for the research was provided by The Hong Kong University of Science and Technology R and D Corporation Limited (RDC) (project number: 21220380S023). Substantial thanks go to Dr. Zhongming Lu for his help in discussing methodologies and to Yuktung Chow for assisting in the field survey.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118072.

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