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Exploring business models for carbon emission reduction via post-consumer recycling infrastructures in Beijing: An agent-based modelling approach

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ABSTRACT

The potential for carbon emissions avoidance through post-consumer recycling has been highlighted in the "Zero-Waste City" initiatives in China, which call for increasing household participation in the community recycling programs. A shift from a facility-oriented strategy to behavior-oriented norm building at the community level provides the local niches for emerging business models in post-consumer recycling. This paper proposes a framework based on the Theory of Planned Behavior to simulate the impact on the participation rate of households in community-based recycling program in the context of different recycling business models in Beijing. Firstly, a questionnaire survey was conducted in 2021 in Beijing ($N = 1153$) to test the key factors which affect household recycling behavior. Secondly, an agent-based model for community-based recycling which was developed in 2016 has been updated to incorporate the institutional change in the development of zero-waste city initiatives. Scenario analysis is adopted to compare the effects of introducing two new business models to the baseline situation that is prevalent at present. The settings for the two new business models represent the diversified directions of the upgrading of urban recycling sector: one is to improve the intelligence of the collection facilities to save labors, and the other is to involve the informal recyclers to provide door-to-door collection services in person so as to save time for the residents. Additional scenario shows the effects of norm-based solutions in combination with the two strategies addressed above in the long run. The simulation results show that the potential for carbon emissions reduction through post-consumer recycling in Beijing can range from 1 million tons per year at the basic scenario to more than 4.5 million tons per year in the community level norm-based solution scenario. In conclusion, the proposal for sustaining the community-based new business models through the capture of value in the carbon emission reduction is put forward as a guideline for urban recycling infrastructure design.

1. Introduction

The potential for carbon emission avoidance through post-consumer recycling has been revealed at both product level (Gielen, 1997; Lauk et al., 2012) and economy-wide with detailed material flow analysis (Ohno et al., 2021). Since cities are increasingly becoming centers of consumption in the global network (Glaeser et al., 2001), the post-consumer recycling activities in a city have deep impacts on both the upstream supply chain and the downstream flows of discarded materials that flow beyond the territory of the city (Chen et al., 2020a).

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Therefore, the transformation of waste infrastructures has been identified as one of the key community-wide systems in cities in low carbon transitions (Ramaswami et al., 2021).

As the by-product of urban lifestyle, the amount of municipal solid waste (MSW), is growing much faster than the rate of urbanization. And, there is a positive correlation between waste generation and income level (World Bank, 2018). The effort to "decouple the waste from the wealth" has demonstrated that the window of opportunity for cities to find better solutions for this fundamental public service of modern cities is critical to achieve the Sustainable Development Goals (SDGs) in "making cities and human settlements inclusive, safe, resilient and sustainable".

China has initiated an ambitious "Zero-waste city" plan that aims to minimize solid waste generation and maximize recycling in urban areas (Gu et al., 2021). A new wave of social movement to promote waste sorting at source in cities has been constructed as a "New Fashion"[1] linking the desire for a better life of individual to the sustainable development of the whole society. In addition, China's pledge to reach peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060, highlights the potential for carbon emission reduction through a systematic optimization in waste management (Xiao et al., 2022). New technologies and business models are emerging to deal with the core challenges in waste reduction, which relate to the normative underpinnings of the current growth model, requiring substantial transition in the value and measurement of economic performance and social welfare. While various economic instruments are applied to provide the incentives for recycling, the social instruments are increasingly recognized in pursuing inclusivity and the environmental justice in this sector (Medina, 2010). How to redesign the urban recycling infrastructure to foster new business models that strengthen the cooperation among all stakeholders? How can the low carbon transition be incorporated with the community-level recycling efforts?

2. Literature review

Local community provides an important environment which can shape people's pro-environmental attitudes and behaviors (Junot et al., 2018; Zhang et al., 2020). Post-consumer recycling depends on consumers' participation behaviors, which can be adapted to specific waste treatment infrastructures and structured recycling programs (Derksen and Gartrell, 1993). Existing research has identified key factors influencing the recycling behavior, and attempted to build models to predict the change of behaviors.

2.1. The application of theory of planned behavior on household recycling

A large body of literature has explored recycling activities among other pro-environmental behaviors through the Theory of Planned Behavior (TPB) (Yuriev et al., 2020), from the standard TPB predictors (Klöckner, 2013; Tonglet et al., 2004), to extended factors, such as moral norm (Botetzagias et al., 2015) and place attachment (Wan et al., 2021). The subjective social norm has been identified as one of the most critical factors that affect the recycling behavior through forging attitudes, beliefs, and values which are helpful in developing a sustainable community in the long run (Ceschi et al., 2021; Griskevicius et al., 2012). Thus, the development of policies based on social norms which facilitate citizen cooperation and match the specific local context is key for improving participation in a recycling program (Chao, 2008; Viscusi et al., 2011). However, such a norm-based solution has a double edge in affecting people's pro-environmental behavior. There is a tipping point in the population when a new behavior is adopted (Nyborg et al., 2016). Before reaching this tipping point, the social norm could prevent people who have a supportive attitude. Effective incentives require scientific supports in measurement and monitoring of these effects to help the norm-based policy in crossing the tipping point and achieve a higher adoption rate of the target activity (Fontecha et al., 2022).

2.2. Contradictions on the social norm in waste sorting in China

The effects of social norm on the recycling behavior in cities of China are vague in existing research. In the participatory research, social norm has been observed as a critical factor affecting the participating rates at a community level (Tong et al., 2018a) as well as to low carbon lifestyle in general (Liu et al., 2021). However, significant correlation between social norm and recycling intention was not found in empirical data from several survey-based studies (Tian et al., 2019; Zhang et al., 2021). Thus, access to recycling facilities and economic incentives received more attention in policy making (Meng et al., 2019; Zhang et al., 2019). Especially, when a new wave of household garbage sorting promotions started across many cities in China from 2019, general supportive attitudes towards recycling have been created among citizens, yet a deviation still exists between willingness and behavior (Kuang and Lin, 2021). Liu et al. (2019) has identified the partial mediating effects of subjective norms on the willingness to classify household waste when addressing the role of public education in the promotion of recycling. And this relation is not moderated by the conscientious personality, which indicates that the subjective norm could relies more on the social relations with other people. Given the dramatic social restructuring from a traditional society of acquaintances to a strangers' one in the fast urbanization, the weak effects of subject norm detected in the empirical studies are rightly reflecting the necessity to reconstruct the social trust system among the new citizens in urban communities. Considering that the influence of economic incentives for recycling has kept decreasing due to income growth in many Chinese cities, norm-based policy has the potential to build garbage sorting habits for citizens in the long run, especially for the younger generation (Abdel-Shafy and Mansour, 2018; Wang and Zhang, 2022).

2.3. Norm-building in the low carbon transition

To encourage pro-environmental behavior, local governments have supported various programs at community-level with the participation of multiple stakeholders (Peng et al., 2021). New business models for "Internet+" recycling are booming to incorporate the digital technology for knowledge sharing and for the provision of incentives with many case studies across different cities in China (Jian et al., 2019; Kurniawan et al., 2021; Wang et al., 2018; Zhou et al., 2021). The potential for carbon emission reduction by waste sorting provides additional value to be captured and shared among different actors along the recycling value chains (Chen et al., 2020b). Besides a financial incentive directly provided to the participating households, such as personal carbon allowances (Fuso Nerini et al., 2021), the carbon indicators also provide a forum for social dialog to build the norm on pro-environmental lifestyle (Wang et al., 2021). On the one hand, the traditional local social network still plays a key role for social mobilization for actions such as waste sorting promotion in local communities in most cities (Pei, 2019; Wang and Zhang, 2022). But on the other hand, new social media creats quite different channels for information sharing and social interactions which can shape the belief, value and attitudes of people towards recycling. Information sharing among people through dynamic social networks is shaping the social norm as well (Chen and Gao, 2021). The impact of social media on the younger generation has been remarkable. Young people spend more time with friends on-line than on social interactions with relatives and neighbors. The leading Internet companies in China now are using creative financial mechanisms to promote the low-carbon lifestyle to attract the attention of the younger generation. Examples include the "Ant Forest" of Alibaba and the "Low Carbon Planet" of Tencent. These tools have been implemented successfully in

[1] https://govt.chinadaily.com.cn/s/201909/10/WS5d8b2fe7498ebcb190579836/shanghai-leads-nation-in-new-era-of-garbage-sorting_1.html

simple activities, such as walking, biking, and using public transportation. However, when it comes to recycling activities, the provision of information and incentives only via platforms is less efficient, for they have to be incorporated in infrastructure and local services to facilitate the participation of residents (Tong et al., 2018b). Therefore, for the social norm to be effective in promoting pro-recycling activities, it has to be embedded in a heterogeneous context constructed both online and offline. The new business models for post-consumer recycling activities emerging in China provide instructive cases for us to understand the social construction of morality in urbanization.

This paper aims at identifying the role of social norm in the formation of new business models for upgrading the urban recycling sector by using insights from participatory social experiments and quantitative measurements from a questionnaire survey. An agent-based model (ABM) based on the TPB is established to illustrate the results of different policy scenarios. Section 3 will explain the model and policy scenarios. Section 4 presents the model results, as well as the potential for carbon emission reduction at the city level in each scenario. In Section 5, we discuss the implications of the research results with comparison to previous research. Finally, policy implications for the upgrading of urban recycling sector are presented in conclusion.

3. Methods

Existing research has pointed out that the social and cultural aspects are crucial in low carbon transition (Sovacool and Griffiths, 2020). However, it is difficult to integrate the social aspects with the highly quantified studies in those material centric assessment of sustainability, such as circular economy (Walzberg et al., 2020). Agent-based Model (ABM) are increasingly used in recent years to study circular economy and low carbon transition scenarios in relation to consumer behaviors (Hansen et al., 2019; Labelle and Frayret, 2018; Walzberg et al., 2021), because it accounts for human decisions and interactions between actors with temporal and systematic aspects (Walzberg et al., 2020), and bridges the theoretical advances in behavioral studies and insights from practices (Tong et al., 2018a). Post-consumer recycling relies on the participating behavior of residents. In order to reveal patterns of complex psychological factors on individual behavior, this study updates the agent-based model based on TPB developed in 2016 (Tong et al., 2018a) with empirical tested functions through the structural equation model analysis on questionnaire survey in Beijing.

3.1. Study area

The research is conducted in Beijing, where 7975 thousand tons household solid waste were collected and disposed through the municipal solid waste management system in 2020, when a city-wide waste sorting at source initiative was launched. Due to the combined effects of COVID 19 and the waste sorting program, the total waste generated from household has decreased by more than 30% in 2020 compared to 2019 (Beijing Bureau of Statistics, 2021), in which the recyclables accounts for nearly 40% (Tong et al., 2021). Fig. 1 shows the spatial distribution of household waste generation in Beijing in 2020 weighted by the residential population at the kilometer grid of the city.

The population of Beijing almost doubled since early 2000s. The local residents concentrate in the inner city with aging infrastructure; while, new immigrants moving in after 2000 mainly live in the new built peripheral areas (Tong and Tao, 2016). As the standardized four streams waste separation system was established, the residents were required to classify the household waste into food waste, recyclables, non-recyclables, and the hazardous, and to put into separate bins. The challenge is how to change the behavior of the residents and establish the habits of waste sorting. Different business models with ICT solutions are emerging to provide additional incentives to recycling (Jian et al., 2019; Wang et al., 2018).

3.2. Modeling framework

In order to reveal the factors affecting the recycling behavior of households and the norm-building effects at the community-level, a combination of participatory experiments and modeling techniques is adopted: first, the insights on current business models for urban recycling come from the participatory observations in two community recycling programs; second, the constructs of the TPB are extended for local perceptions on community; third, the decision rules and utility functions are developed to describe households behavior and decision processes based on TPB and incentives provided by different business models; finally, an ABM developed with python is created with decision rules for agents based on their characteristics, including age and residential status, to estimate the participation rate at the community level. The results of ABM are used with the geographical variants in demographic characteristics in sub-district level in Beijing to upscale the community level estimation to the city level for the calculation of carbon emission reduction potential from post-consumer recycling.

3.2.1. Participatory observation in community recycling program

The insights on the urban recycling business models are extracted from participatory observations on community recycling programs in two residential communities in Beijing since 2012. The first one was in a newly built residential community in north suburb of Beijing from 2013

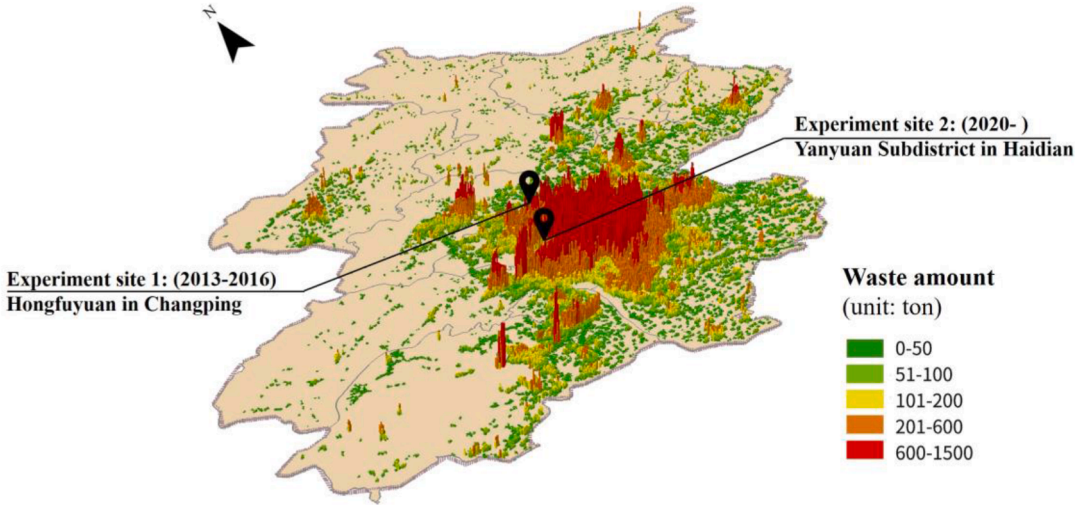

Fig. 1. Spatial allocation of annual household waste generation at kilometer grid in Beijing.

to 2016 (Tong et al., 2018a), where the IT solutions were used to provide incentives to households participating in the community recycling program. This experiment incorporated three key elements that influenced similar business models which developed afterwards across many cities in China: (1) door-to-door services that the households can order the collection service at home through smart phone applications; (2) hardware facilities (recycling bins) in the neighborhood, where the residents can discard their recyclables by themselves, and the workers will collect the recyclables from the facilities routinely; (3) incentives to households based on the weight of recyclables they submit. For example, the service-oriented business models are adopted by Huge in Hangzhou and Aifenlei in Beijing. The recycling companies receive financial supports from the local governments to provide the door-to-door collection services in the community with the aid of Internet solution. The difference between the new business model and the traditional informal recyclers is that the role of the collector is not only to do the collection work, but also to provide face-to-face guidance to the residents to improve the quality of waste classification. And all recyclable waste generated at household will be collected, including those cheap materials, which will be otherwise sent to landfill or incineration, such as glasses, foamed plastics, and so on, for the revenue from recycling these materials cannot cover the cost for collection. In 2022, Aifenlei has served 1009 communities in 6 districts in Beijing, covering more than 720,000 households, and collected more than 110 thousand tons of recyclables.

On the other hand, Aobag, a social enterprise started the community-based recycling program in Chengdu, adopted the facility-oriented strategy, focusing on the development of hardware facilities with improved intelligent technologies in order to save labor costs for the door-to-door services of collectors. Thus, the market value of the recyclables could be used to provide economic incentives to the participating households, and not relying on the financial support from the local government. They now have established intelligent recycling cabins in 66 communities in Beijing.

We worked with Aifenlei and Aobag to get data of participation rate (the share of households that have submission records in a given time period to the number of households that have registered in that system in a community) of different business models at the community level in Beijing. We also started a program in Yanyuan subdistrict with the support from the local administration in 2020. Yanyuan, an old residential community in the inner city with aging infrastructure, adopted the standardized four-stream waste separation system as required by the municipal administration. We tried to bring different business models in this old community, and interacted directly with various stakeholders during the experiment.

3.2.2. *Structural equation model of the TPB+*

In order to upscale the insights from participatory observation in specific communities, a questionnaire survey at the city level was developed based on an extended TPB framework (Ajzen, 1991). This theoretical framework has been widely used in the study of waste sorting in China (Meng et al., 2019; Shi et al., 2021; Tong et al., 2018a). We incorporated the general concepts and measurements in existing studies. The contribution of this research is to study the influence of local interactions among households, recyclers, and infrastructures which form the local environment where the behaviors are taking place. The aim is to estimate the participation rate in a community when interventions are introduced by different business models.

Fig. 2 shows the conceptual framework of the model. Besides the factors studied in existing research, the interventions in different business models are introduced through the Community Perception (CP), and include the perceived participation rate through the social network, the perceived conditions of recycling facilities, and the accessibility to information on recycling. We used structure equation analysis to test the behavior deviation among different age groups and the residential status. We organized the study to test two hypotheses: (1) the younger generation, whose age below 40, will be more affected by the (digital) network of their non-local friends rather than their local neighbors; and (2) the local residents (people with local *hukou* in Beijing) will be more affected by the peer pressure from social norm. These two hypotheses represent the changing social norm in a rapidly urbanizing China. When it comes to intergenerational changes in behavior, interactive hyper-spatial social media have more impacts on youngsters; while for institutional evolution, the *hukou* system has been stated as the main factor for the exclusion of non-local residents. Table 1 shows the survey items in the questionnaire which are related to participatory recycling behaviors.

The questionnaire survey was conducted in Beijing in 2021. Before the major investigation, two pilot surveys were conducted: the first one was in Yanyuan in 2020 with 149 interviewees through face-to-face communication. These interviewees are mainly aging people who are actively participating in our recycling programs in the community. The second one was conducted through an on-line survey to quantitatively test the rationality of the questionnaire items with 120 samples from Shanghai and 114 samples from Beijing. Items without significant differences between these two cities were kept to guarantee that the questionnaire could be generalized to more cities in China.

The content of questionnaire was designed according to the TPB with three sections: (1) household garbage sorting behavior; (2) affecting factors; and (3) demographic characteristics. The main part of the investigation was conducted in Beijing with sampling in terms of demographics of Beijing through webchat. A total of 1612 questionnaires

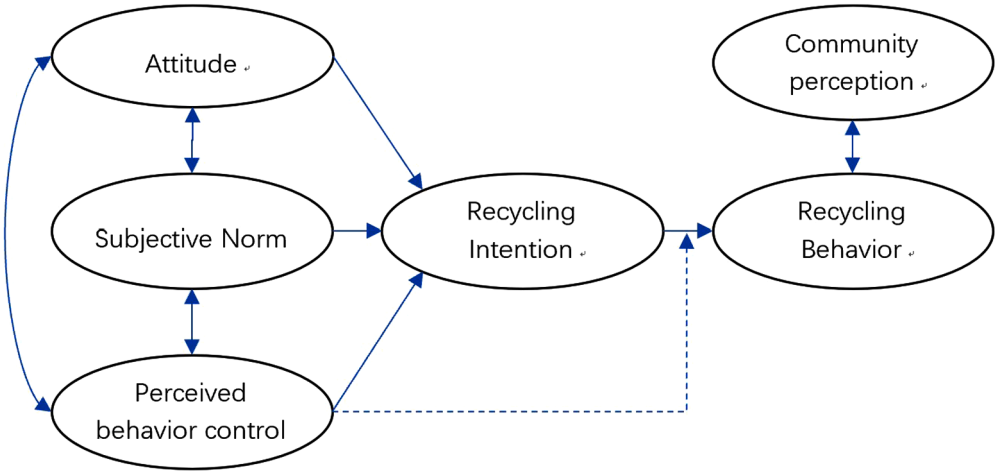

Fig. 2. Conceptual framework – the agent-based model based on TPB+ for the household solid waste (HSW) classification behavior.

Table 1
Survey items related to participatory recycling behaviors.

Variable	Item	Reference
Attitude (AT)		
environmental awareness	I think environmental protection is important.	
value perception	I think waste separation is sensible and rewarding.	Nguyen et al. (2015)
environmental benefits recognition	Waste separation at source is good for the environment.	Yuan et al. (2016)
environmental incentives sensitivity	I would prefer to participate in waste separation if I can get environmental incentives.	
economic incentives sensitivity	I would prefer to participate in waste separation if I can get economic incentives.	
Subjective Norm (SN)		
perceived influence from family & friends	My family and friends think that I should separate my household waste.	Ioannou et al. (2013)
perceived influence from neighbors	People in my community think that I should separate my household waste.	Yuan et al. (2016)
Perceived Behavioral Control (PBC)		
time adequacy	Waste separation doesn't take too much of my time.	Nguyen et al. (2015)
space adequacy	Waste separation doesn't take too much of my living space.	Tonglet et al. (2004)
classification knowledge	I know how to separate my household waste.	Tonglet et al. (2004)
Community Perception (CP)		
perceived participation rate	Most people are involved in waste sepaation in my community.	
perceived facility condition	Waste separation facilities are in good condition in my community.	
perceived facility sufficiency	Waste separation facilities are sufficient in my community.	
publicity and guidance	Waste separation publicity and guidance is adequate in my community.	

was collected, in which 1153 were valid. Table 2 shows the detailed information of the samples. The aged people ('61 and above') is under represented in this on-line questionnaire survey because of the low accessibility to Internet of this group. However, their characteristics of behavior has been highly represented in the on-site face-to-face interviews and pilot surveys in our experimental study in the communities. Furthermore, from the observation in the communities, we found that most aging people are used to the traditional way of selling recyclables to the informal collectors. They often find it technically difficult to use the information technology in the new business models, either using the intelligent facilities or ordering the door-to-door service through the smart phone applications. Since the main aim of the questionnaire survey is to find out the possibility to improve the participation rate of young generation in recycling with new business models, the age structure of the questionnaire survey is reasonable.

Table 2
Descriptive statistics (N = 1153).

Demographic variables		Frequency	Proportion
Gender	Male	561	48.7%
	Female	592	51.3%
Age	0–18	159	13.8%
	18–25	234	20.3%
	26–40	385	33.4%
	41–60	342	29.7%
	61 and above	33	2.9%
Education level	High school and below	557	48.3%
	College graduate	488	42.4%
	Postgraduate and above	108	9.4%
Family annual income (10,000 RMB/ Year≈1,583USD/Year)	5 and below	167	14.5%
	5–10	242	21.0%
	10–20	362	31.4%
	20–50	286	24.8%
	50 and above	96	8.3%
Residential status	Local	689	59.8%
	Non-local	464	40.2%

The model was tested with the partial least squares structural equation model (PLS-SEM) in IBM SPSS Amos 23.0, which can handle multiple influencing factors and explore the relationships between manifest variables and latent variables. SEM has been wildly applied to explore resident recycling behavior (Yang et al., 2022). The PLS-SEM is distribution-free without strong assumptions about data distribution, and it can be used for modeling that includes formative measurement components (Hair et al., 2016), which is fitful in our analysis for integrating the insights from field observation with the data of questionnaire survey.

3.2.3. *The agent-based model at community level*

The model tested by SEM has been used to build the ABM to simulate the effects of introducing the new business models on the participation rate of recycling in the communities. The ABM developed in 2016 (Tong et al., 2018a) was re-coded in Python and updated with the investigation results. All coefficients in the model have been replaced with the results of the structure equation model based on the questionnaire survey.

The new model takes the level of a residential community as a unit of behavior system. Each household is one agent to make behavior decisions. They can do three categories of actions: (1) to generate waste; (2) interacted within their neighbors and friends; and (3) discard the recyclable waste with three choices – mixing the recyclables with the unrecyclable wastes and throwing into the waste bins for residues destining to incineration, sending the well sorted recyclables to the fixed collection facilities, or giving the recyclables to door-to-door collectors. The households choosing to separate the recyclables from other waste will be defined as recyclers, no matter they choose to use the fixed collection facilities or the door-to-door collectors. The participation rate will be the share of recyclers in the total households in this community.

3.3. *Scenarios for the new business models*

Based on the participatory observations, the upgrading of the recycling sector through new business models can be described in two interrelated dimensions (Fig. 3). The current standard municipal waste management system (as the lower-left purple square in Fig. 3) provides the baseline reference, in which the concentrated waste disposal infrastructure, such as the incineration plants and food waste disposal centers, are operated at the municipal level. The informal recycling sector is separated from the formal waste management system, and relies on a vast network of immigrant recyclers to collect the recyclable waste from households, and to sort them into secondary materials for recovery. In fact, the whole recycling system relies on the economic value of the recyclable materials. Research has shown that it is challenging to sustain this informal system due to increasing labor costs and environmental standards in China (Steuer et al., 2018; Tong et al., 2021).

Fig. 3 shows the theoretical concepts for the upgrading of the urban recycling sector. The two crossed arrows represent the dimensions which could upgrade the informal recycling sector in China by incorporating it into the urban waste management system.

The horizontal dimension represents the type of the new business model which could rely more on facilities or on face-to-face services offered by the collectors. The vertical dimension represents the impacts of spatial allocation of infrastructure facilities for recycling in cities. Compared to the standard municipal waste disposal facilities, new business models have a more dispersed allocation of facilities to be closer to their customers in residential communities. The recycling company would like to establish concentrated regional recycling centers to generate the economies of scale for recycling, However, if the value of

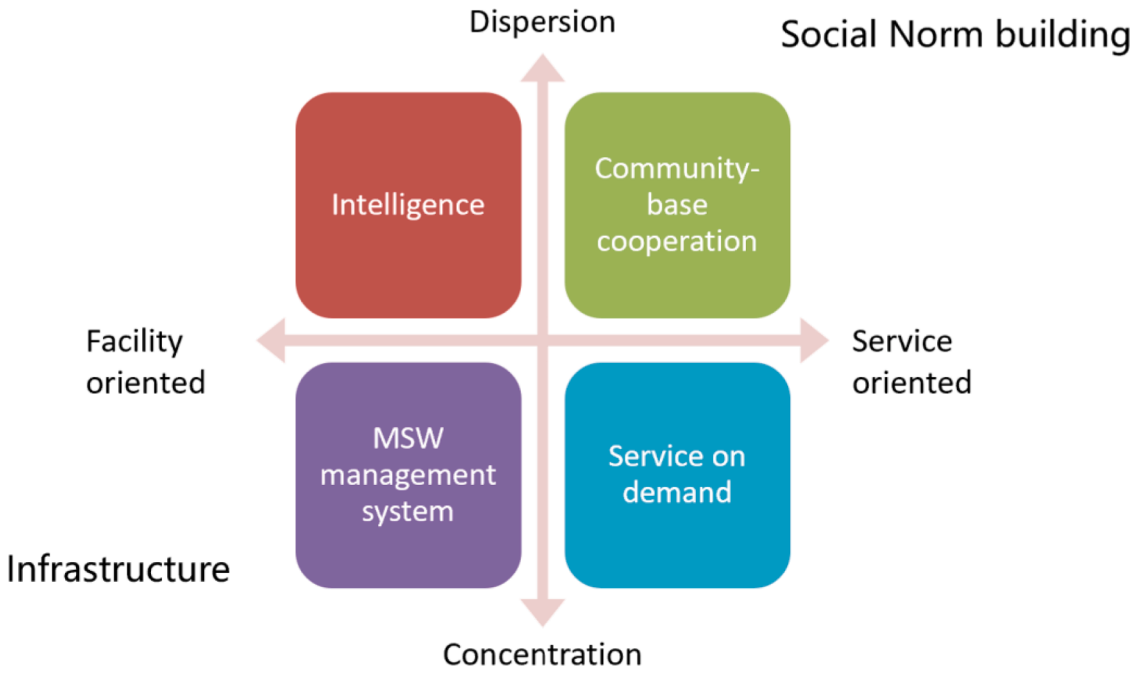

Fig. 3. The two dimensions for the upgrading of urban recycling sector. (MSW: municipal solid waste).

waste reduction can be captured and shared within the communities, we expect better performance of resources efficiencies through more dispersed activities of reusing, repairing and recycling that close to the residents.

With these two dimensions, four scenarios can be identified with reference to the typical community samples selected with our research partners in Beijing to test the model. The scenarios settings have been showed conceptually in Table 3. Scenario A refers to the basic scenario, in which no new business models are adopted, thus no additional incentives are provided to either consumers or recyclers. Scenario B adopted the intelligent facilities to improve the attractiveness of the fixed recycling facility in the community. The additional economic incentives are directly given to the residents who are sorting the waste correctly and deliver to the facility by themselves. Section C adopted the service-oriented business model, which is upgraded from the traditional informal recycling sectors. With the subsidy from the local government, these business model can employ workers to provide door-to-door collection services to the residents through orders by the mobile phone APPs. According to the contract from the local government, they should collect both recyclable waste and hazardous waste from the households without consideration of the price of the secondary materials. The subsidy is associated with the number of households covered by the recycling company. The local government also set the target for participation rate. Therefore, the company will give some economic incentives to the residents based on the weight of recyclable waste.

Neither scenario B nor scenario C considers the norm building through social interactions. Therefore, Scenario D is developed according to the perception of local conditions and the degree of willingness to change as the social norm expected. The effect was investigated through the association between the questions on the willingness to classify the waste and the perceived participation rate of neighborhoods or friends (indicated by the five-degree Likert measure on to what extent the respondent agrees that “Most people are involved in waste separation in my community”). By increasing the weight of this factor, Scenario D simulate the situation, in which the community has established common sense on waste sorting and build the habits to send the classified recyclables to the facilities or the collectors. The range of parameter configuration in each scenario is derived from the structural equation models with cases of typical sample communities. Each scenario has been run randomly on the Exploratory modeling and analysis (EMA) workbench for 1000 times to get the distribution of participation rates.

Table 3
The scenario settings.

	Scenario ABasic scenario	Scenario BIntelligent facility	Scenario CService-oriented	Scenario DNorm-based Policy
Additional economic incentives for collector	normal	normal	high	normal
Additional economic incentives for residents	0	high	0	normal
Facility condition	low	high	–	high
Advocation	low	normal	high	high
Convenience for residents	normal	normal	high	high
Impact of social norm	normal	normal	normal	high

3.4. The potential for carbon emission reduction through recycling

The results of ABM scenarios will be used as the reference of participation rates in the calculation of carbon emission reduction potential at the city level. The sub-district level demographic characteristics are used to represent spatial variance in the communities throughout the city.

The calculation of composition and quantities of household waste generated in Beijing can be found in our previous paper (Tong et al., 2021). The waste generated in each community in ABM is the product of the population of the community (derived from the population census) and the average waste generation per capita in Beijing.

The potential carbon emission reduction was calculated from the weight of collected recyclable materials through waste classification in households. The calculation formula is as follows:

$$\mathrm{CER} = \sum_{1}^{n} W_i * ef_i \quad (1)$$

in which, CER is the overall potential for carbon emission reduction; W_i is the weight of the i composition in the recyclable waste, including paper, plastics, glasses, metals, and textiles; ef_i is the emission reduction efficient of the i composition of recyclables. The emission reduction efficient of metals, plastics, and papers follows the method used by Cudjoe et al. (2021). Other materials are calculated from China Products Carbon Footprint Factors Database (CCG, 2022).

4. Research results

4.1. The TPB+ model of the community recycling behavior

The result shows that the community perception has significant positive effects on the classification behavior in a direct way without the mediation effects of the classification intention. The results of the model tested by SEM are shown in Fig. 4. The effects of the classical factors in TPB, including attitudes, subjective norms, and perceived behavior control, are confirmed. By adding the factor of Community Perception, the standard deviation that explained by the model can be increased from 39% to 43%. The standard factor loadings of the four observable variables (perceived participation rate, perceived facility condition, perceived facility sufficiency, and face-to-face guidance) for the latent variable of community perception are higher than the observable variables of the three classical TPB factors, indicating that constructed concept of community perception in this model is good.

Additionally, the age and residential status are identified as significant factors effecting the waste classification behaviors in the analysis on the questionnaire survey data. We use two questions to distinguish the local residents from non-local residents - one is "whether you have local *hukou* (registered local permanent residence)?", the other is "do you know most of your neighbors?" The answers to these two questions are highly related. Therefore, we use "local *hukou*" as indicators for local residents, while the rest are taken as immigrants. The data shows significant difference between local residents and non-local residence in factors affecting their household waste classification behaviors. Compared to non-local residents, the local residents are more willing to classify their household waste, feeling more pressures from social norms, and less caring the economic incentives and the time for doing the classification. Generally, the social norm is more influential within the local residents than the immigrants. As to the factor of age, the result confirms that the elder residents feel more external expectations on waste classification from their neighbors and friends, and are more willing to participate.

4.2. ABM simulation results for the four scenarios at community level

Four scenarios on the upgrading of the recycling sector by introducing new business models are illustrated according to the selected sample communities from our own field studies and our research partners. We set the range of the variables in the model according to the real situation that the introduction of new business models could bring in, which have been explained in detail in Section 3.3. Thus, the model can generate the results of participation rate at community level with randomized values according to the configuration for each scenario.

The distribution of randomized 1000 results in each scenario are compared in Fig. 6. The result is generally stable. In the Basic Scenario, there are no introduction of any new business models. The residents are using the standardized waste bins in the community provided by local sanitary companies. The majority of the households choose to mix the recyclables with the residues sending for incineration. The rest (around 10%) of the households gather the recyclables to sell to the informal collectors nearby in a traditional way.

In the Intelligent Scenario, the upgrading of the recycling sector will

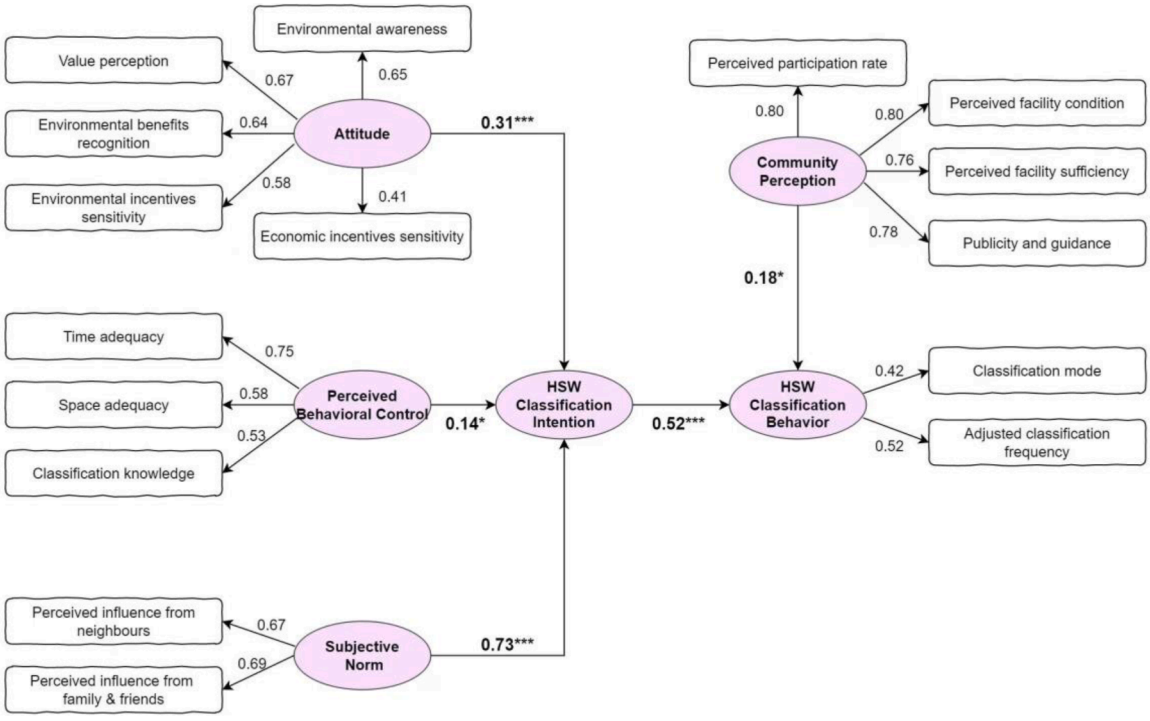

Fig. 4. Test result of structure equation. References of the model framework in Fig. 1.
Note:
The number beside the arrow lines are path coefficients between the key variables of the model; the number without asterisks indicate the standard factor loading of the observable variables to the latent variables.
* statistically significant at 0.1, *** statistically significant at 0.05.

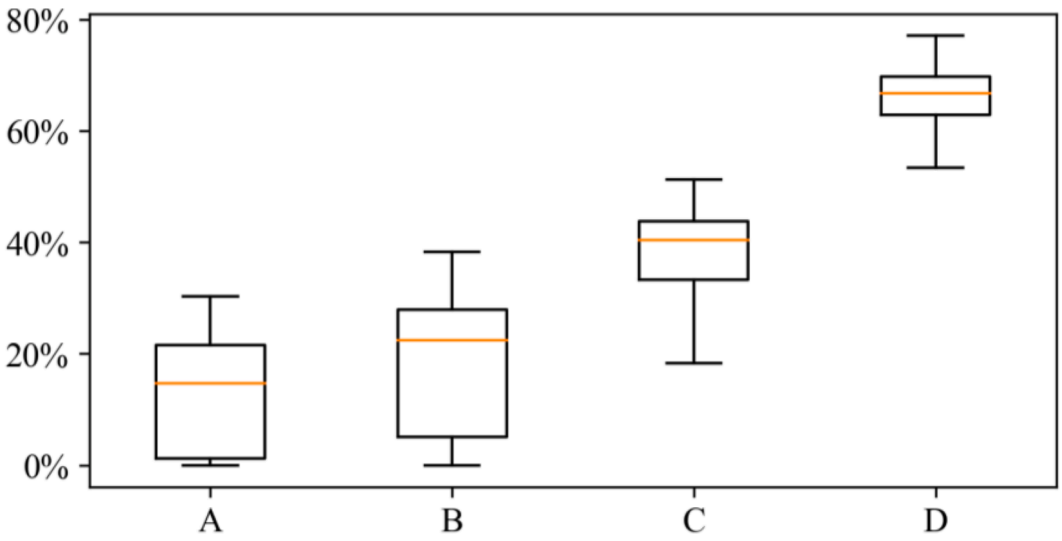

Fig. 5. The distribution of participation rates for the three ways of recyclable waste discarding for 1000 randomized results of the four scenarios in comparison.

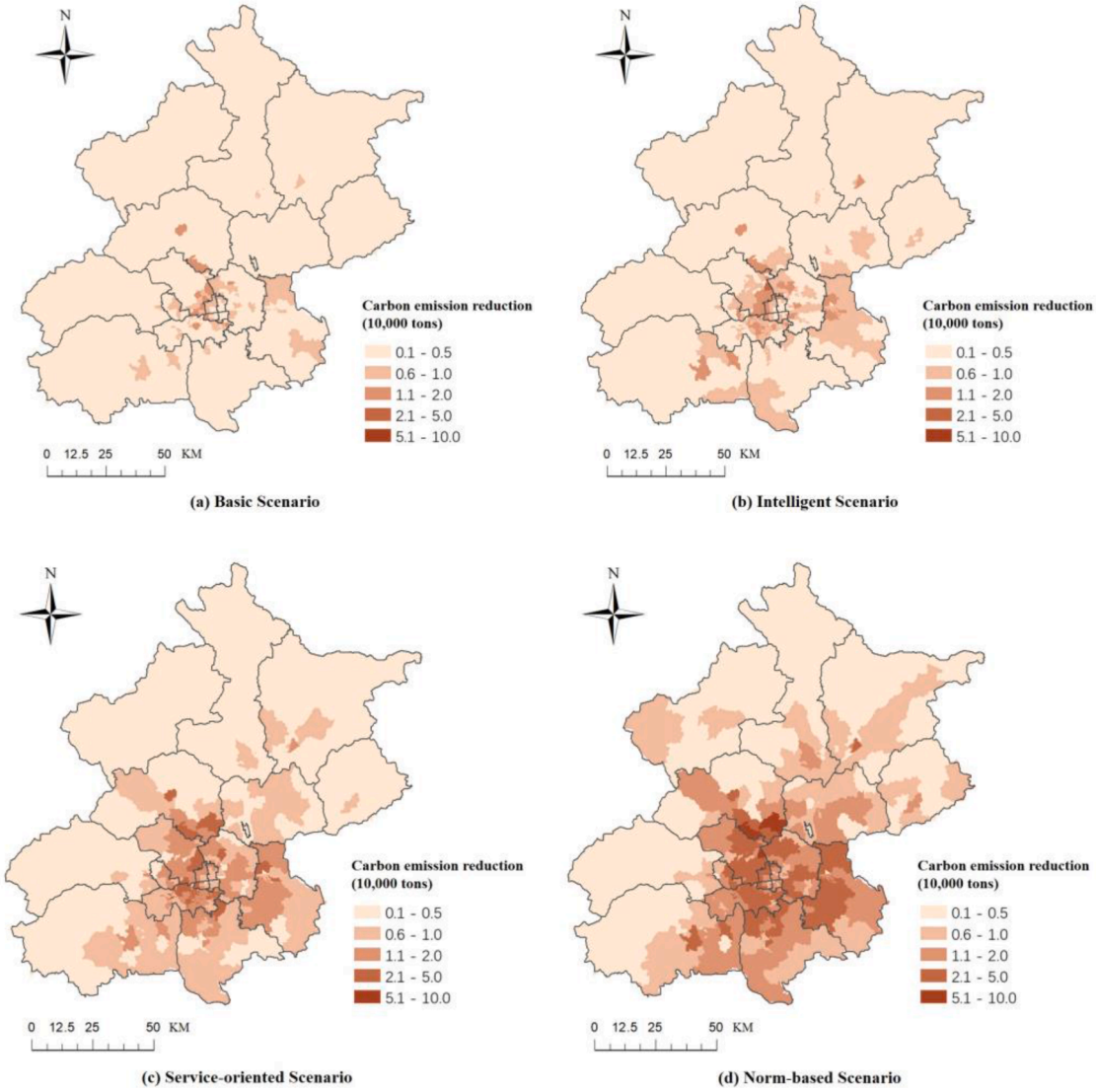

Fig. 6. The spatial distribution of carbon emission reduction through household recycling in four scenarios in Beijing.

deploy fixed recycling facilities with intelligent technology in the community where the residents can send their sorted recyclable waste and getting rewards. This scenario can reach 20% of the participation rate without additional subsidies from local government. The informal recyclers keep providing door-to-door collection services as usual but they are mainly focused on the recyclable goods of high economic value. The location of the facilities in this scenario was randomly assigned according to the service distance required by the planning of recycling facilities of the local government. The location of the facilities can be influential for the households closer to the facilities will be more likely to participate.

In the Service-oriented Scenario, the upgrading of the recycling sector formalizes the informal recyclers who provide door-to-door services to collect all the recyclable waste from households. With subsidies provided by the local government to the recycling companies, the residents can be offered not only more convenient ways to recycle but also additional economic incentives to participate. Thus, the participation rate can reach up to 50%.

In the Norm-based Scenario, both the fixed facilities and the door-to-door services are provided to the communities. The effects of social norm in this scenario is high in that people choose to recycle as much as possible, when they believe that their neighbors and friends are participating. The fixed facilities receive recyclables of low value without any direct economic incentives, while the waste collectors provide door-to-door services for people in need. The participation rate in this scenario can exceed 70%.

4.3. The potential for carbon emissions reduction at city level

The ABM at community level was applied for all residential communities in each subdistrict in Beijing. The demographic characteristics of each subdistrict, including the number of households, the age structure, and local/nonlocal residents' ratio, are derived from the latest census data published in 2021. With the participation rate estimated at community level, Table 5 shows the potential for carbon emission reduction in four scenarios at city level in Beijing, which reveals the possibility to save the carbon emissions on the upstream supply chain by using the recyclable materials to replace virgin materials. This is a rough estimation to demonstrate the potential for carbon emissions reduction through the improvement of the participation rate in recycling activities at a city level. In 2021, the total carbon emission trade volume in Beijing was 25.3 million tons, in which about 0.6 million tons are through the trade of China Certified Emission Reduction (CCER). The potential of carbon emission reduction through improving the participation rate of household recycling could reach one fifth of the annual carbon emission trade volume of the city. This potential provides additional value for local recycling programs, which is critical in the upgrading of urban recycling sectors in transition.

Fig. 6 shows the spatial distribution of the potential carbon emission reduction through household recycling in four scenarios in Beijing calculated from the ABM. Obviously, the urban center with high population density has high potentials. Additionally, service-oriented business models induce higher participation in the inner city, where the communities have higher portion of elder residents. The norm-based policy is expected to involve the younger generation and new immigrants' household mainly living in new developed area around the urban fringe. To unlock the hidden potential in household recycling, proper infrastructure for collection and recycling is required with new business models that can facilitate the participation of all residents.

Table 5
The potential for carbon emission reduction in four scenarios for in Beijing.

		Basic scenario	Intelligent scenario	Service-oriented scenario	Norm-based scenario
Carbon emission reduction (10,000 t CO2)	paper	46.7	66.5	113.2	198.9
	plastic	28.9	41.1	70	122.9
	textile	13.4	19	32.4	57
	metal	12.3	17.6	29.9	52.5
	glass	5.3	7.6	13	22.8
Overall reduction (10,000 t CO2)		106.6	151.9	258.6	454.1

5. Discussion

5.1. Upgrading recycling infrastructures towards a low carbon city

Research has pointed out that waste sorting programs can be perceived as social interactions among many stakeholders, including the recycling sector, the households, and the government (Peng et al., 2021). Most studies dealt with various factors that shape the behavior of individuals in a way that is disconnected from the local context. Recent studies addressed place-specific factors focusing on psychological attachments to the living space which can theoretically influence the attitudes of residents towards recycling (Pei, 2019; Wan et al., 2021). In this research, such a place-based approach is incorporated into the upgrading of the urban recycling sector.

Currently, the use of the intelligent technologies in fixed recycling facilities faces the competition from the door-to-door services provided by the informal recycling system. The policies focusing on the economic incentives to residents strengthen such competition. Consumers can enjoy more convenience with door-to-door services. However, without subsidies from the local government, the formalisation of the existing recycling system is financially unsustainable. In the Norm-based Scenarios, the two business models can be integrated with each other. The fixed recycling facilities in the community reduce the burden of recyclers, who can provide door-to-door services for people in need. The target is to divert the recyclables from waste flows towards recycling chains. As we have seen in the case of Aihuishou, they tried to add intelligent facilities in some of the communities. Such integrated solutions can hardly be standardized for all communities. With the general indicators on resources circularity being increasingly applied for city sustainability, the innovation niches can be created for new business models that can effectively use the different strategies based on the local context.

5.2. Building new norms and value for recycling in urban transition

Currently, the majority of municipal solid waste has been treated in incineration plants to produce electricity and heat in Beijing. From the view of sanitation and waste reduction, the incineration is an efficient way to deal with the burnable waste even though it can have substantial health impacts (e.g. production of dioxin-like compounds during start-up operations) when proper measures are not taken (Zero Waste Europe, 2018). The environmental impacts of the incineration can be substantial since it has been estimated that one ton of burning waste can lead to approximately one ton of CO_2 emissions (Zero Waste Europe, 2021). However, the environmental burden of incineration might not be as easily perceived by the residents, unless they live nearby. Furthermore, incineration have no effects on the rationale of current economic development which relies on mass consumption of natural resources. It also promotes a lock-in effect by demanding a constant supply of waste as input.

In order to promote post-consumer recycling, we need better infrastructure that support the business model linking an individual's interests on the local wellbeing with the common welfare at large. The Ant Forest program has shown the capability to construct a pro-environmental social norm online through social network of friends which expands beyond the spatial limits of local communities that link more than 550 million people in doing small things for the environment. The task for recycling is more complex, requiring the coordinated efforts

from different stakeholders at different stages along the recycling value chain. As the carbon footprint of products and their corresponding supply chains are increasingly being considered by companies' commitment towards carbon neutrality, the value of post-consumer recycling will have a larger chance to be embodied in the moral norms that across the labor specialization on the value chains, and create positive feedback loops for the development of norm-based policy in future.

6. Conclusion

The potential to reduce carbon emissions through recycling has attracted the attention of regional recycling programs in China. This study reveals the significant potential for carbon emissions reduction by improving the participation rate of households in recycling activities. Changing the behavior of households is not only a problem of social influence, but also of infrastructure provision with proper business model which can facilitate recycling activities in communities. Even with widely supportive attitudes towards recycling after several public education campaigns, inducing a pro-recycling behavior is still challenging. Besides the provision of economic incentives, social norms can be a powerful lever for positive change in the long run, especially in current urban society of China. After more than 30 years of fast urbanization, the patterns of social interactions have changed dramatically. The transition towards low carbon cities provides the opportunity for building pro-environmental norms among the new generation of urban residents.

The provision of recycling infrastructures is not only the responsibility of the municipal administration, but also creating niches for new business models via social cooperation at the community level. The emerging new technologies and business models in urban recycling sector have diversified into different directions: (1) using intelligent technology to cut down labor costs; and (2) including the informal recycling sector to create decent jobs with value-added services. These two directions should be integrated in that the facilities armed with intelligent technologies reduce the burden of recyclers, who can provide door-to-door services for people in need. The innovation in business models are expected to effectively use the different strategies based on the local context. The provision of infrastructure for the community-based recycling programs can actually foster cooperation among stakeholders. Here, the local community is the living-lab for collaborative social experiment with all stakeholders.

CRediT authorship contribution statement

Xin Tong: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. **Haofan Yu:** Data curation, Formal analysis. **Ling Han:** Conceptualization, Data curation. **Tao Liu:** Data curation, Formal analysis, Writing – review & editing. **Liang Dong:** Conceptualization, Funding acquisition. **Filippos Zisopoulos:** Conceptualization, Writing – review & editing. **Benjamin Steuer:** Conceptualization, Writing – review & editing. **Martin de Jong:** Supervision, Conceptualization, Funding acquisition, Writing – review & editing.

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

Data will be made available on request.

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