



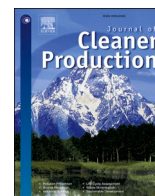
An integrated framework for dual-scale assessment of recyclable waste resource potential and environmental–economic benefits in a Chinese

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An integrated framework for dual-scale assessment of recyclable waste resource potential and environmental–economic benefits in a Chinese megacity

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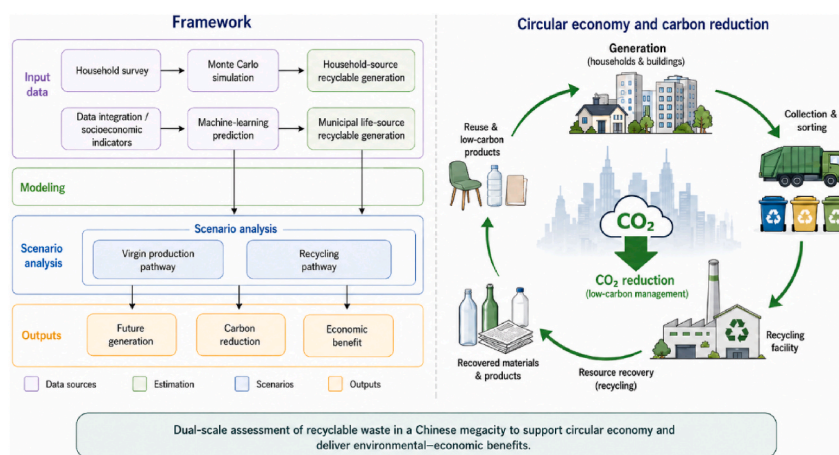
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HIGHLIGHTS

- A dual-scale framework is developed to link household-source and municipal life-source recyclable waste generation.
- Household survey data and Monte Carlo simulation are integrated to quantify micro-scale recyclable waste generation with uncertainty.
- Machine-learning models are applied to predict city-scale recyclable waste generation using multi-source socioeconomic indicators.
- Material-dependent environmental and economic outcomes are identified across glass, plastics, and paper.
- The framework provides a transferable tool for recyclable waste accounting and low-carbon urban waste management.

GRAPHICAL ABSTRACT



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ABSTRACT

Municipal solid waste management is a key pathway for urban carbon mitigation and resource efficiency, yet recyclable waste generation across different urban sources remains insufficiently quantified. This study develops a dual-scale analytical framework to assess recyclable waste resource potential and environmental-economic benefits in a Chinese megacity. The framework integrates household-source measurement with municipal life-source recyclable generation prediction to characterize recyclable resource potential from complementary accounting perspectives. Household-source recyclables are quantified using two rounds of household surveys conducted in summer and winter 2025, involving 448 households, combined with Monte Carlo simulation, while municipal life-source recyclables are predicted using machine-learning models with multi-source socioeconomic variables. Scenario-based life cycle assessment is further applied to evaluate carbon and economic performance under virgin and recycling pathways.

The results demonstrate substantial differences between the two accounting scales. Household-source recyclable generation was estimated at 251,800, 966,500, and 1,103,500 tons for waste glass, plastics, and paper, respectively, whereas municipal life-source recyclable generation reached 614,760, 3,100,000, and 3,109,600 tons, corresponding to 2.44-, 3.21-, and 2.82-fold higher estimates. These differences reflect the broader system boundary of municipal life-source accounting, which incorporates recyclable flows beyond household sources, rather than indicating a direct inconsistency between the two accounting scales.

The environmental and economic assessments further reveal strong material-dependent heterogeneity. Waste plastics and paper exhibited more stable environmental-economic co-benefits, whereas waste glass showed greater sensitivity to collection efficiency, transportation distance, and market conditions. The proposed framework provides a complementary multi-scale approach for robust recyclable waste accounting and supports data-driven urban low-carbon management.

1. Introduction

Municipal solid waste (MSW) management is increasingly recognized as a critical pathway for urban carbon mitigation, resource conservation, and circular economy development (Chen et al., 2020; Ding et al., 2021; Gómez-Sanabria et al., 2022). Across the entire waste management chain—including generation, collection, transportation, treatment, and disposal—MSW is closely associated with greenhouse gas emissions and resource consumption, making it a key leverage point for urban low-carbon transition (Chen et al., 2020; Sun et al., 2024; Zhang et al., 2024; Zhang et al., 2024). Rapid urbanization, rising consumption levels, and changing household lifestyles have further accelerated the generation of recyclable waste in cities, creating both environmental pressures and opportunities for secondary resource recovery (Lu et al., 2024). In China, the implementation of the “dual carbon” strategy and recent waste recycling policies have further emphasized the need to improve waste reduction, resource recovery efficiency, and system-level decarbonization (Ding et al., 2021; Liu et al., 2024a; Wen et al., 2023).

Household-source recyclables, particularly waste glass, plastics, and paper, represent a major but often under-characterized resource stream, with relatively mature recycling pathways and available environmental-economic assessment data, as their generation and recovery are strongly influenced by household behavior, informal collection systems, and local waste management practices (Li et al., 2024; Tang et al., 2022; Yu et al., 2022). Previous studies have extensively applied life cycle assessment (LCA) and material flow analysis (MFA) to evaluate the environmental performance of MSW systems, demonstrating that recycling-oriented strategies can significantly reduce greenhouse gas emissions and energy consumption (Liu et al., 2024b; Wen et al., 2023; Yuan et al., 2020). At the city scale, LCA-based studies have shown that waste classification behavior and sorting accuracy can strongly influence system-level environmental outcomes (Liu et al., 2024b; Yin et al., 2024; Yuan et al., 2020). For plastic waste in particular, recent research has expanded system boundaries to full life-cycle “production–consumption–recycling” systems (Chen et al., 2023), revealing that mechanical recycling provides superior carbon reduction potential compared with incineration and landfill. Integrated environmental–energy–economic assessment frameworks have further been developed to support decision-making in urban waste systems (Liu et al., 2024a).

Despite these advances, three key limitations remain in existing

research. First, most studies rely heavily on macro-scale statistical data, formal collection records, or industrial recycling datasets, while empirical micro-scale evidence from households remains insufficient (Gu et al., 2021; Yu et al., 2022). This limitation may lead to systematic underestimation of recyclable waste generation, particularly when informal collection, direct reuse, scavenging, or pre-collection diversion are not fully captured in official statistics (Hidalgo-Crespo et al., 2024; Li et al., 2024). Second, although low-value recyclables such as glass and certain plastics constitute a large fraction of MSW streams, their environmental and economic performance remains insufficiently characterized (Ji et al., 2023). Their recycling efficiency is often constrained by low market value, unstable collection systems, transportation distance, and processing costs (Dai, 2024; Zhang et al., 2024). Although scenario-based studies indicate that these materials can still deliver substantial carbon reduction benefits under optimized systems (Ji et al., 2023; Xiao et al., 2023), their real-world recovery rates remain limited, especially in developing urban contexts (Alhassan et al., 2020; Roustae et al., 2020). Third, current assessment frameworks are often insufficiently integrated, focusing on single-dimensional indicators or deterministic analyses, while neglecting behavioral heterogeneity, socioeconomic drivers, system uncertainty, and cross-scale consistency (Ferronato et al., 2021; Liu et al., 2024b; Paes et al., 2020; Yuan et al., 2020). In particular, limited attention has been given to uncertainty propagation in waste generation and recycling benefit estimation (Barahmand and Eikeland, 2022; Chen et al., 2023).

To address these gaps, this study develops a dual-scale analytical framework that integrates household surveys data, Monte Carlo simulation, machine learning prediction, and scenario-based environmental-economic assessment. A megacity in southern China (Guangzhou) is selected as the case study. First, household-source recyclable generation is quantified using two rounds of door-to-door surveys conducted in summer and winter 2025, combined with Monte Carlo simulation to characterize uncertainty. Monte Carlo simulation enables probabilistic representation of key input variables and is particularly suitable for uncertainty quantification in complex environmental systems (Barahmand and Eikeland, 2022; Chen et al., 2023; Martín-Pascual et al., 2020). Second, machine learning models—including XGBoost, Random Forest, and Bayesian Regression—are employed to predict municipal life-source recyclable generation based on multi-source socioeconomic and structural variables. Machine learning methods have demonstrated strong capability in

capturing nonlinear relationships in MSW systems, particularly for variables such as population, GDP, and consumption behavior (Hoy et al., 2022; Xia et al., 2022; Zhang, C. et al., 2022). Third, scenario-based life cycle assessment is applied to compare virgin material production and recycling pathways under environmental and economic dimensions (Dai, 2024; Liang et al., 2023; Liu et al., 2023; Luan et al., 2021).

The contributions of this study are threefold. First, this study provides high-resolution household-level empirical evidence to characterize residential recyclable waste generation and associated uncertainties, offering direct insights into household-source recyclable flows. Second, this study establishes a dual-scale analytical framework integrating household-source measurement and municipal life-source prediction to evaluate recyclable resource potential from complementary accounting perspectives. Specifically, household-scale assessment captures residential generation characteristics, while municipal-scale prediction estimates broader urban recyclable resource potential by incorporating multi-source socioeconomic variables. Third, this study translates recyclable waste generation estimates into material-specific environmental and economic implications for waste glass, plastics, and paper, providing decision-support insights for differentiated recycling strategies in megacities.

2. Methodology

The technical approach of this study is presented in Fig. 1. Two complementary accounting scopes were established to characterize recyclable waste generation from different urban perspectives: household-source recyclables and municipal life-source recyclables. These two scopes represent different system boundaries and are not intended to describe identical waste streams (see Fig. 2).

Household-source recyclables refer to waste glass, plastics, and paper directly generated by residents' households and quantified through

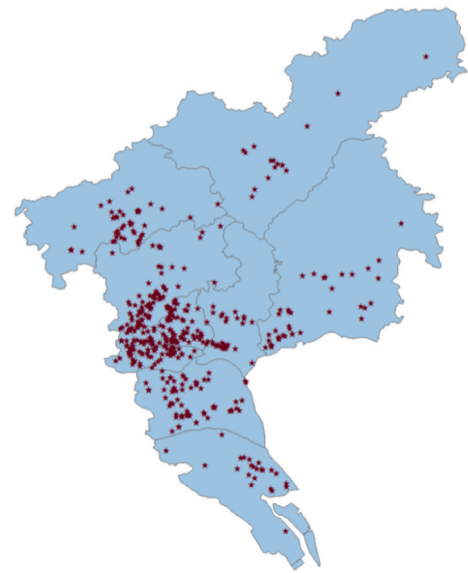


Fig. 2. Spatial distribution of household-source recyclable generation across Guangzhou based on household survey data.

door-to-door tracking surveys. Municipal life-source recyclables refer to the broader recyclable waste stream generated from daily-life activities within the city, including households, public spaces, schools, government and enterprise units, commercial service settings, and other institutional or community sources. Accordingly, household-source assessment provides micro-scale empirical observations of residential recyclable generation, whereas municipal life-source prediction supports city-scale resource potential evaluation through integration of socioeconomic and structural variables.

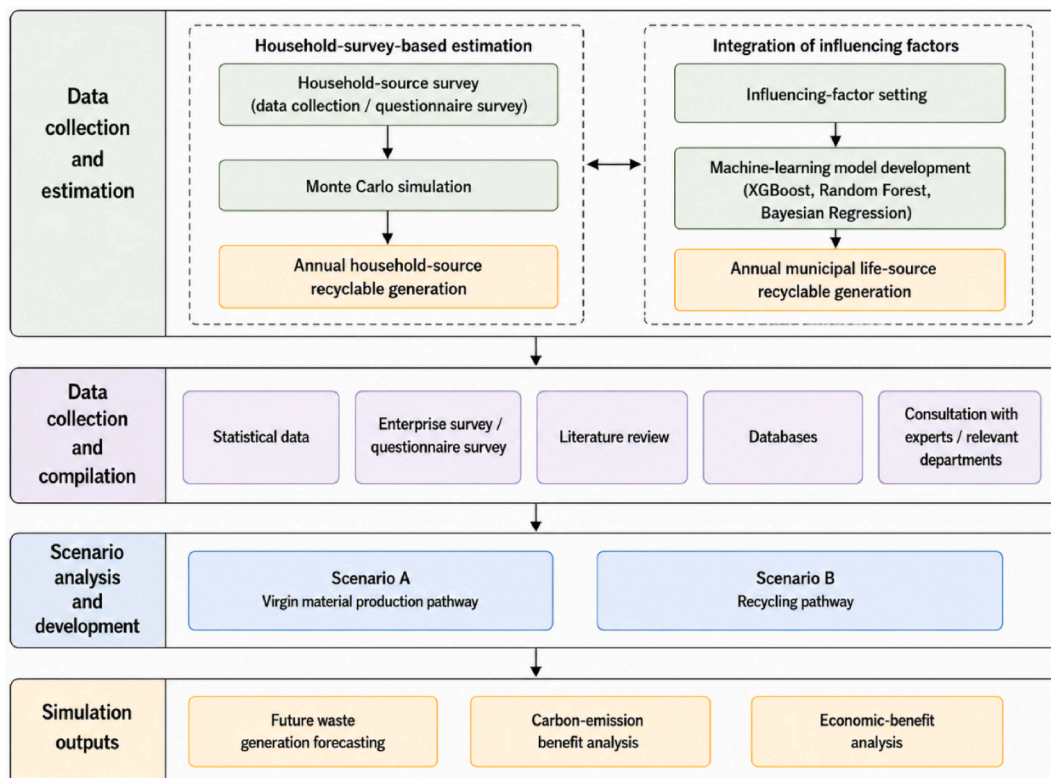


Fig. 1. Methodological framework for the dual-scale assessment of recyclable waste integrating household survey, Monte Carlo simulation, machine-learning prediction, and scenario-based environmental-economic analysis in a megacity.

Based on this distinction, household-source recyclable data were collected through door-to-door tracking and questionnaires from 448 households across all administrative districts of Guangzhou. Each household completed two rounds of waste classification and weighing records, yielding 896 valid household-level observations. The annual generation of household-source recyclables was first estimated using household survey data and Monte Carlo simulation. Subsequently, multi-source socioeconomic and structural variables were integrated to develop machine-learning models for predicting total municipal life-source recyclable generation, covering waste glass, plastics, and paper. Two scenario pathways, namely the virgin material production pathway and the recycling pathway, were then established to assess carbon-reduction and economic benefits. Finally, future trends in waste glass, plastics, and paper generation and their resource-recovery potential were projected by integrating population growth, economic development trends, and the established predictive framework to support long-term policy planning. Future household-source recyclable generation was projected based on demographic and socioeconomic development scenarios rather than direct extrapolation of historical trends. Population growth and economic development indicators were selected as key drivers of recyclable waste generation, with projected values summarized in Table S7.

2.1. Data collection

This study conducted two rounds of door-to-door tracking surveys of household-source recyclable waste during the summer and winter of 2025 to capture contrasting seasonal conditions. The survey used 1 week as the basic time unit, with each household as the smallest unit of investigation, covering all administrative districts of the city, and a total of 551 households were sampled. To ensure the data's representativeness and statistical validity, the sample design was based on the city's population distribution and statistical sampling principles. The sample size was determined using the simple random sampling method, and the calculation formula is as follows:

$$n = \frac{N * Z^2 * p(1-p)}{E^2 * (N-1) + Z^2 * p(1-p)} \quad (1-1)$$

Where:

n: Sample size,

N: Total number of households in the city (Guangzhou Bureau of Statistics, 2026),

Z: Confidence coefficient (1.96 for a 95% confidence level),

P: Estimated proportion (0.5),

E: Allowable margin of error (5%).

Based on the above parameters, the theoretical minimum sample size is 384 households. Considering sample loss and invalid questionnaires, the final survey sample size was set at 551 households (Ahmed, 2024). The survey combined short-term tracking and repeated monthly recording, in which each household recorded the generation of waste glass, plastics, and paper during two survey rounds. Specially designed garbage bags and electronic data sheets were provided to guide residents in weighing and recording waste classification data, including waste generated outside the home. Professional surveyors conducted regular follow-ups to ensure data accuracy and completeness. Ultimately, 448 of the 551 sampled households completed both the summer and winter rounds of waste classification and weighing, yielding 896 valid household-level observations. Although these two rounds captured contrasting seasonal conditions, spring and autumn were not independently sampled; therefore, some residual seasonal variability may remain in the annualized estimates.

In addition to the door-to-door survey, the study also included field visits, literature reviews, questionnaire surveys, and expert interviews. Multi-source data from the National Bureau of Statistics, provincial and municipal statistical bureaus, and relevant authorities were integrated

to provide the data foundation for the subsequent construction of the machine-learning-based prediction model, supporting the assessment of resource utilization potential.

2.2. Monte Carlo simulation

Monte Carlo Simulation is a random simulation method based on probability statistics, suitable for handling problems with complex structures and uncertainty characteristics (Zhang, 2021). Its core lies in constructing a probabilistic model and performing large-scale random sampling on key variables according to predefined distributions to generate simulated samples. Through statistical analysis, the true solution of the problem is approximated, achieving uncertainty quantification and result visualization (Jamroz and Williams, 2020; Papadopoulos and Yeung, 2001).

This study is based on the Central Limit Theorem (CLT). Under the condition that the sample size is sufficiently large, even if the original data does not follow a normal distribution, the distribution of the sample mean can be approximated as normal, thereby supporting statistical inference and simulation modeling based on the normality assumption (Heyde, 2014). Its mathematical expression is as follows:

$$X_n \sim N(\mu_n, \sigma_n^2) \quad (1-2)$$

In the implementation of the model, the mean and standard deviation of the daily waste glass, plastics, and paper recycling amount per household are set based on the door-to-door survey data, and 50,000 random samples are taken to estimate the annual generation and its fluctuation range, constructing the probability distribution. To measure the relative dispersion of the data, the Coefficient of Variation (CV) is introduced as a dimensionless indicator, which is suitable for comparing data of different scales and conducting stability analysis (Arachchige et al., 2022). The Monte Carlo simulation was used to characterize and propagate the variability observed in the household survey rather than to independently validate the survey-derived estimates.

2.3. Machine-learning prediction of municipal life-source recyclable generation

To predict the total generation of municipal life-source recyclables in Guangzhou, including waste glass, plastics, and paper, and to identify their key influencing factors, this study adopted machine-learning models including XGBoost, Random Forest, and Bayesian Regression. These models were selected to compare predictive performance under different data structures and sample-size conditions.

First, XGBoost is an ensemble learning algorithm based on the Gradient Boosting Tree (GBT) framework, which iteratively trains weak classifiers and accumulates optimized residuals to continuously improve the overall predictive performance of the model (Chen and Guestrin, 2016; Li, 2022). Second, the Random Forest (RF) model is based on the Bagging concept and consists of multiple independent decision trees. The model constructs subtrees through random sampling of both samples and features, and outputs the final results by majority voting for classification or averaging for regression (Xu et al., 2023). Each decision tree operates independently and can run in parallel, ensuring high computational stability, strong noise resistance, and good generalization ability (Mentch and Hooker, 2016). Finally, Bayesian Regression (BR) is established on the principles of Bayesian statistics, where the posterior distribution of parameters is inferred from prior and likelihood functions (Gelman et al., 1995). This method performs robustly under small sample sizes and multicollinearity conditions, quantifies prediction model uncertainty, and provides credible intervals, thereby enhancing model interpretability and reliability (Adepoju and Ojo, 2018; Kruschke, 2021). To further evaluate the stability and predictive performance of the models, the Bootstrap resampling method was adopted (Efron and Tibshirani, 1994). This method performs random sampling with

replacement on the original dataset to enhance the models' generalization and stability. Particularly for small-sample data, it effectively reduces the risk of overfitting and ensures model reliability under different data distributions (Hesterberg, 2015).

In addition, to explore the relationship between waste glass generation and multiple factors, a correlation heatmap was constructed, and the Pearson Correlation Coefficient (PCC) was used to quantify the linear relationships between variables. The PCC is calculated based on the covariance between variables, with a range from -1 to 1 . The closer the absolute value is to 1 , the stronger the correlation, while the sign indicates the direction of the correlation (positive/negative). The PCC expression is as follows:

$$R_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (1-3)$$

By calculating the PCC values between input variables and the target variable, the main factors influencing waste glass generation are identified, providing support for model construction and policy development (Ishfaq et al., 2023) (see Table 1).

This study is based on relevant data published by the national and municipal governments from 2015 to 2025, collecting and organizing information related to the generation of waste glass, plastics, and paper. The data were standardized and missing values were filled, and an analysis variable set was constructed. As shown in Table 2, multiple key variables were selected, including the national production and recycling amounts of solid waste, the city's resident population, per capita GDP, per capita disposable income, as well as factors such as policies, the pandemic, the catering industry, and consumer behavior (Budach et al., 2022; Nijman et al., 2022).

2.4. Evaluation of resource recovery benefits

This study establishes scenario pathways to compare the differences between primary material production and recycled material recovery in terms of carbon emissions and economic costs, thereby providing a comprehensive evaluation of the environmental and economic benefits of solid waste recycling. The recycling pathway was defined as a maximum resource-recovery potential scenario, assuming that all identified household-source recyclable materials could be collected and recycled. This assumption was adopted to estimate the theoretical upper-bound potential of environmental and economic benefits rather than to represent current recycling performance.

Table 1
Distribution of valid household samples across municipal districts.

District	Population (10,000 persons)	Proportion of Total City Population (%)	Number of Surveyed Households
District A	96	5.1	23
District B	176.83	9.4	42
District C	113.3	6.0	27
District D	223.8	11.9	53
District E	366.68	19.5	87
District F	122.21	6.5	29
District G	172.87	9.2	41
District H	282.29	14.5	67
District I	96.79	5.1	23
District J	73.26	3.9	18
District K	158.67	8.4	38

Table 2

Influencing factors and variable descriptions for predicting municipal life-source recyclable generation in Guangzhou Bureau of Statistics, 2026

Variable	Influencing Factor	Description
X1	National Solid Waste Generation	Annual total generation of solid waste nationwide (unit: 10,000 tons)
X2	National Solid Waste Recycling	Annual total amount of solid waste recycled nationwide (unit: 10,000 tons)
X3	COVID-19 Impact	Categorical variable representing behavioral impacts after the COVID-19 pandemic (mild, moderate, severe)
X4	Resident Population of the City	The permanent population size of the city, one of the main factors affecting waste generation
X5	Per Capita GDP of the City	Reflects the level of regional economic development, which may influence consumption patterns and waste generation
X6	Per Capita Disposable Income	Indicates residents' consumption capacity, indirectly affecting the frequency of product use and waste generation
X7*	Policy Influence	Categorically coded policy indicators related to waste classification, circular economy, green development, and resource recycling.
X8	Catering Industry Influence	The impact of catering industry development on the consumption of glass containers, paper packaging, and plastic products
X9	Consumption Change	Variations in residents' consumption patterns and demand, which may affect the generation of waste glass, plastics, and paper products
X10	Industrial Output Variation	Fluctuations in industrial output reflecting changes in demand for plastic, paper, and certain glass products in industrial production
X11	Other Potential Influencing Factors	-

Note: X7* represents categorically coded policy information derived from publicly available government policy documents related to waste classification, circular economy, green development, and resource recycling during 2015–2025. The qualitative policy information was classified according to policy measures, policy categories, and major policy orientations, and converted into numerical features using a unified categorical encoding approach. This variable represents different policy conditions rather than policy intensity or implementation effectiveness.

The carbon reduction benefit is defined as the difference in CO₂ emissions per unit product between the two production pathways, whereas the economic benefit represents the cost difference per unit product between the two routes.

The data utilized in this study were derived from literature, databases, statistical yearbooks, and field investigations, encompassing carbon emission data associated with fossil fuel combustion, industrial processes, and electricity and thermal energy consumption. All data were systematically integrated life-cycle-based carbon accounting framework. Economic costs were determined based on market prices during the survey period and include both direct and indirect costs related to raw materials, energy, and equipment. The assessment was conducted based on the avoided impacts of primary material production and the corresponding benefits from recycling utilization. The functional unit was defined as 1 ton of recovered recyclable material entering the recycling pathway. Material-specific environmental and economic parameters were obtained from published studies, databases, and market information.

The uncertainty of environmental and economic benefits was evaluated by integrating uncertainty from both recyclable waste generation and environmental-economic assessment parameters. Specifically, the uncertainty ranges of household-source generation obtained from Monte Carlo simulations and the prediction uncertainty associated with municipal life-source recyclable generation were incorporated into subsequent carbon-reduction and economic-benefit assessments. The household-source recyclable generation estimates derived from Monte Carlo simulation were used to quantify residential-scale environmental and economic potentials, whereas the predicted municipal life-source

recyclable quantities from the machine-learning model were used to evaluate broader city-scale resource-recovery potential. This approach enabled the propagation of uncertainty from recyclable resource quantification to final environmental and economic outcomes.

The Cumulative Distribution Function (CDF) was employed to describe the cumulative probability of variables across different value ranges. In this study, the CDF illustrates the probability distribution of environmental and economic benefit outcomes obtained from 50,000 Monte Carlo simulations, reflecting the probabilistic characteristics of recycling benefits under uncertainty. Compared with a single mean value, the CDF provides a more comprehensive depiction of the data distribution, supporting uncertainty characterization and benefit assessment under uncertain conditions.

2.4.1. Carbon emission reduction benefit assessment

Life Cycle Assessment (LCA) is a widely applied methodology for evaluating environmental impacts, systematically tracing the entire process of a product from raw material extraction, manufacturing, and use to final disposal. It enables a comprehensive comparison between recycling and conventional production pathways in terms of carbon emissions and energy efficiency (Hetherington et al., 2014; Liu et al., 2022; Owsianiak et al., 2018). Based on the LCA framework, this study quantifies the differences in carbon emissions between primary production and recycling pathways for three typical recyclable materials, including waste glass, plastics, and paper, and evaluates the carbon reduction potential of their resource recovery. The carbon reduction benefits of glass, plastic, and paper recycling under different data sources are summarized in Tables S1–3.

2.4.2. Economic benefit analysis

Traditional economic evaluation methods are often insufficient to capture uncertainties within complex systems. To address this limitation, this study applies Monte Carlo simulation to randomly sample key cost parameters, including raw material procurement, processing, and transportation—to estimate the fluctuation range of recycling costs and to derive the expected values and confidence intervals of economic benefits.

Based on a cost accounting framework, a comprehensive cost model was established, incorporating raw material inputs, energy consumption, labor expenses, and equipment maintenance, thereby enabling a systematic comparison of the economic performance between recycling and primary production pathways (Chukwudi and Ogunedo, 2019; Lessard et al., 2021). The economic costs of glass, plastic, and paper recycling derived from different data sources are summarized in Tables S4–6.

3. Results and discussion

3.1. Annual generation of household-source recyclables

According to the household survey data, the annual generation of household-source waste glass, plastics, and paper in Guangzhou reached 251,800 tons, 966,500 tons, and 1,103,500 tons, respectively, in 2025, all showing notable spatial disparities (Fig. 3). As illustrated in the spatial distribution map, District E consistently ranks first, with glass and paper generation of 56,600 tons (22.51%) and 206,000 tons (18.7%), respectively, while plastics rank second at 160,700 tons (16.63%). Districts D and H also maintained relatively high levels across all three waste categories, which is consistent with their relatively high population density and intensive commercial-residential activities (Landau and Binder, 2021). District E, as one of the city's largest areas with a dense population and frequent commercial activities, generates significantly more recyclables than other regions. Districts D and H, characterized by strong economies and high concentrations of commercial and residential facilities, also exhibit elevated waste generation levels. In contrast, Districts J and I, with lower population densities and relatively limited commercial activities, show comparatively lower waste generation.

These spatial patterns indicate that household-source recyclable generation is closely associated with population density, commercial activity intensity, and mixed residential–commercial land use, suggesting that district-level heterogeneity should be considered when designing collection and sorting strategies.

Based on the probability distribution parameters derived from the household survey data, 50,000 simulations were conducted to characterize annual generation and its uncertainty ranges. The simulations generated probability distributions for the annual household-source generation of waste glass, plastics, and paper in 2025. As presented in Fig. 4, the 95% confidence intervals were 238,600–264,900 tons for waste glass, 932,000–1,000,900 tons for waste plastics, and 1,093,900–1,113,000 tons for waste paper, with standard deviations of 6,700, 17,500, and 4800 tons, respectively. Because the Monte Carlo input parameters were derived from the household survey, the simulated central estimates are expected to remain close to the survey-derived values. Therefore, the simulation results are interpreted as uncertainty characterization rather than independent validation of the household survey.

3.2. Machine-learning prediction of municipal life-source recyclable generation

After considering various socioeconomic, demographic, policy-related, and consumption-related factors, this study used monthly data as the modeling unit and employed XGBoost, Random Forest, and

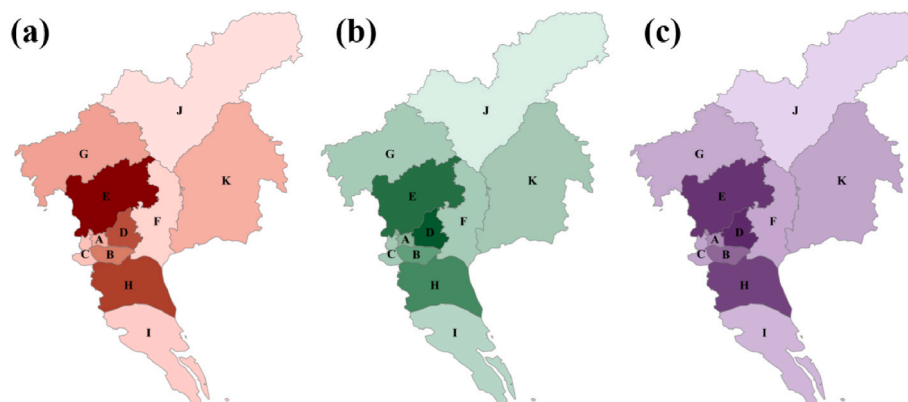


Fig. 3. Annual generation and spatial distribution of household-source recyclables: (a) glass, (b) plastics, and (c) paper.

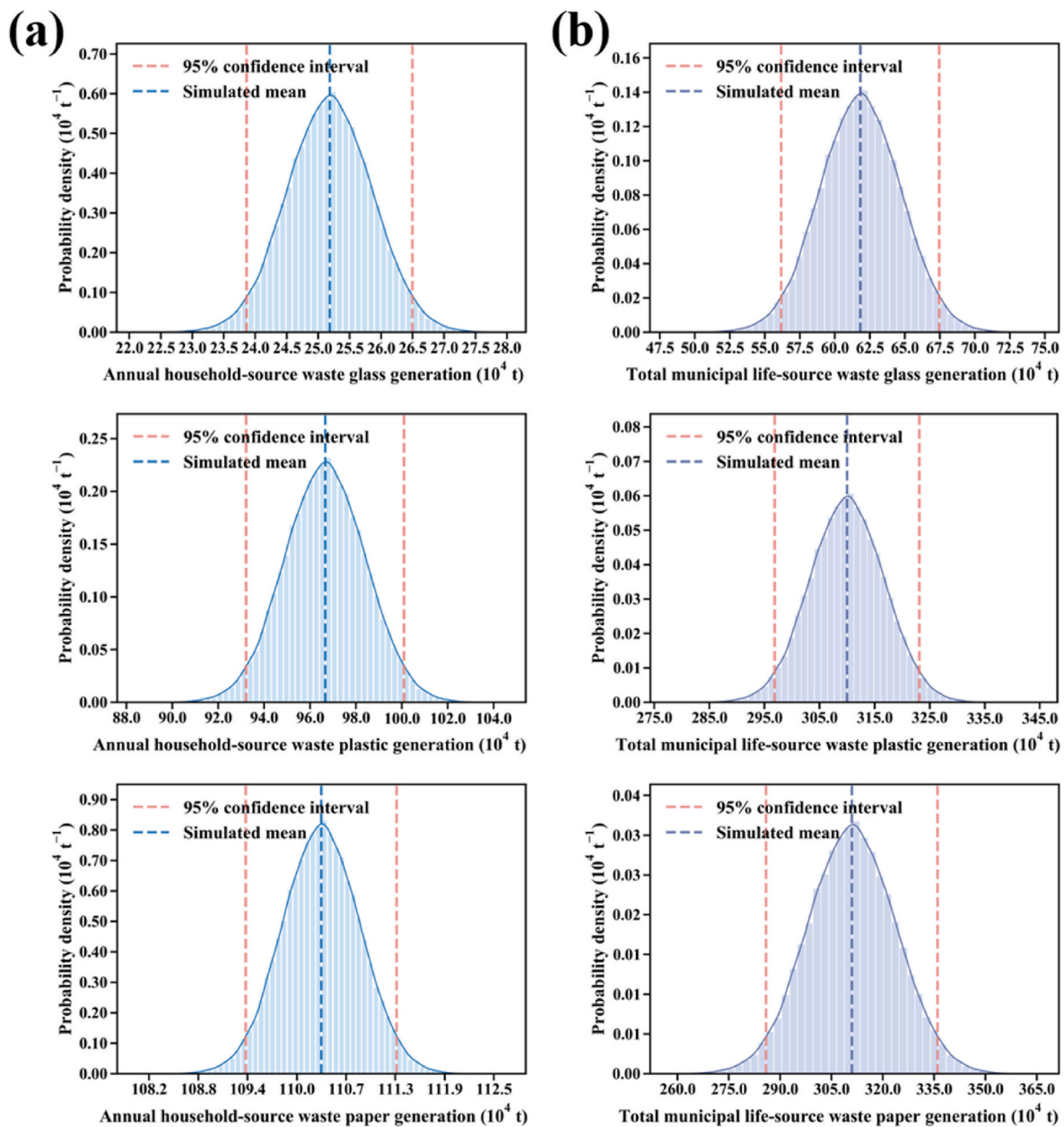


Fig. 4. Monte Carlo simulation results for (a) household-source recyclable generation and (b) municipal life-source recyclable generation of glass, plastics, and paper. Based on 50,000 Monte Carlo simulations.

Bayesian Regression models to estimate the total generation of municipal life-source recyclables in Guangzhou, focusing on waste glass, plastics, and paper. The detailed information regarding dataset characteristics, input variables, model configuration, and prediction framework is summarized in Table S10. To verify the robustness and reliability of the model predictions, the Bootstrap resampling method was applied, performing 3000 repeated random sampling calculations for the machine-learning models. Model performance was evaluated using the coefficient of determination (R^2) and root mean square error (RMSE), while Bootstrap-derived standard deviations were used to characterize prediction uncertainty.

The standard deviations of the predicted generation of waste glass, plastics, and paper were derived to quantify the variability of the model outputs. The model results showed that the XGBoost model predicted the total municipal life-source generation of waste glass, plastics, and paper to be 614,760, 3,100,000, and 3,109,600 tons, respectively, with standard deviations of 16,200, 154,800, and 57,300 tons. The Random

Forest model yielded predicted values of 610,120, 3,123,350, and 3,194,600 tons, with standard deviations of 17,000, 88,200, and 42,400 tons, respectively. The Bayesian Regression model produced predictions of 614,590, 3,272,020, and 3,356,080 tons, with standard deviations of 81,100, 136,500, and 259,300 tons, respectively.

The detailed model-performance metrics, including training and testing R^2 and RMSE values, are provided in Table S8. Overall, all three models showed strong predictive performance, while XGBoost exhibited more balanced predictive performance across glass, plastics, and paper, supporting its selection as the representative model for subsequent prediction and influencing-factor analysis. Although category-specific models showed different advantages, the objective of this study was not to identify the optimal algorithm for each individual recyclable category, but to establish a consistent prediction framework for cross-material resource assessment. A unified XGBoost framework improves methodological consistency and enhances the comparability of subsequent evaluations of recyclable resource potential, carbon-reduction

potential, and economic benefits (see Fig. 9).

Fig. 5 presents the comparison between the observed and predicted generation of waste glass, plastics, and paper in Guangzhou, obtained using the XGBoost, Random Forest, and Bayesian Regression models during both the training and testing phases. In the training dataset, all models exhibited strong fitting accuracy. During testing, Bayesian Regression yielded the lowest prediction errors for waste glass (RMSE = 0.0888) and waste plastics (RMSE = 0.4312), while Random Forest performed best in predicting wastepaper (RMSE = 0.3966). The predicted municipal life-source generation further confirms the scale gap between household-source observations and city-scale recyclable flows. The radar chart in Fig. S1 further compares the training and testing R^2 values of the three machine-learning models, further illustrating the relatively balanced predictive performance of XGBoost across waste glass, plastics, and paper. As shown in Fig. 10, the heatmap reveals strong correlations among population density, per capita GDP, and per capita disposable income. Together with policy influences, these variables were therefore retained as key explanatory factors in the subsequent prediction and scenario analysis.

The predicted municipal life-source generation was substantially higher than the household-source estimates for all three materials, confirming a marked scale gap between direct household observations and city-scale recyclable flows. This scale dependence suggests that accounting approaches relying solely on household-level observations

or formal collection records may fail to capture broader urban recyclable flows, particularly when non-household daily-life sources and informal collection pathways are not fully captured.

It should be noted that the individual contributions of commercial, institutional, and public-space sources to the observed scale differences were not separately quantified in this study. Future studies integrating detailed waste-flow surveys and municipal collection records could further decompose urban recyclable generation by source category and improve the attribution of different recyclable streams.

Based on the 95% confidence intervals of annual household-source recyclable generation for waste glass, plastics, and paper (238,600–264,900 tons, 932,000–1,000,900 tons, and 1,093,900–1,113,000 tons, respectively), 50,000 Monte Carlo simulations were performed to evaluate the carbon-reduction benefits between the virgin and recycling pathways.

As shown in Figs. 6 and 7, carbon emissions arise from multiple sources, including fossil-fuel combustion, process emissions, and electricity and heat consumption. To provide a visual comparison of these emission coefficients, Fig. 6 presents the unit carbon-emission ranges of virgin production and recycling pathways, together with the corresponding carbon-reduction effects for waste glass, waste plastic, and waste paper. Furthermore, to clarify the internal sources of these emission differences, Fig. 7 illustrates the carbon emission contribution pathways of the three recyclable categories, including glass production

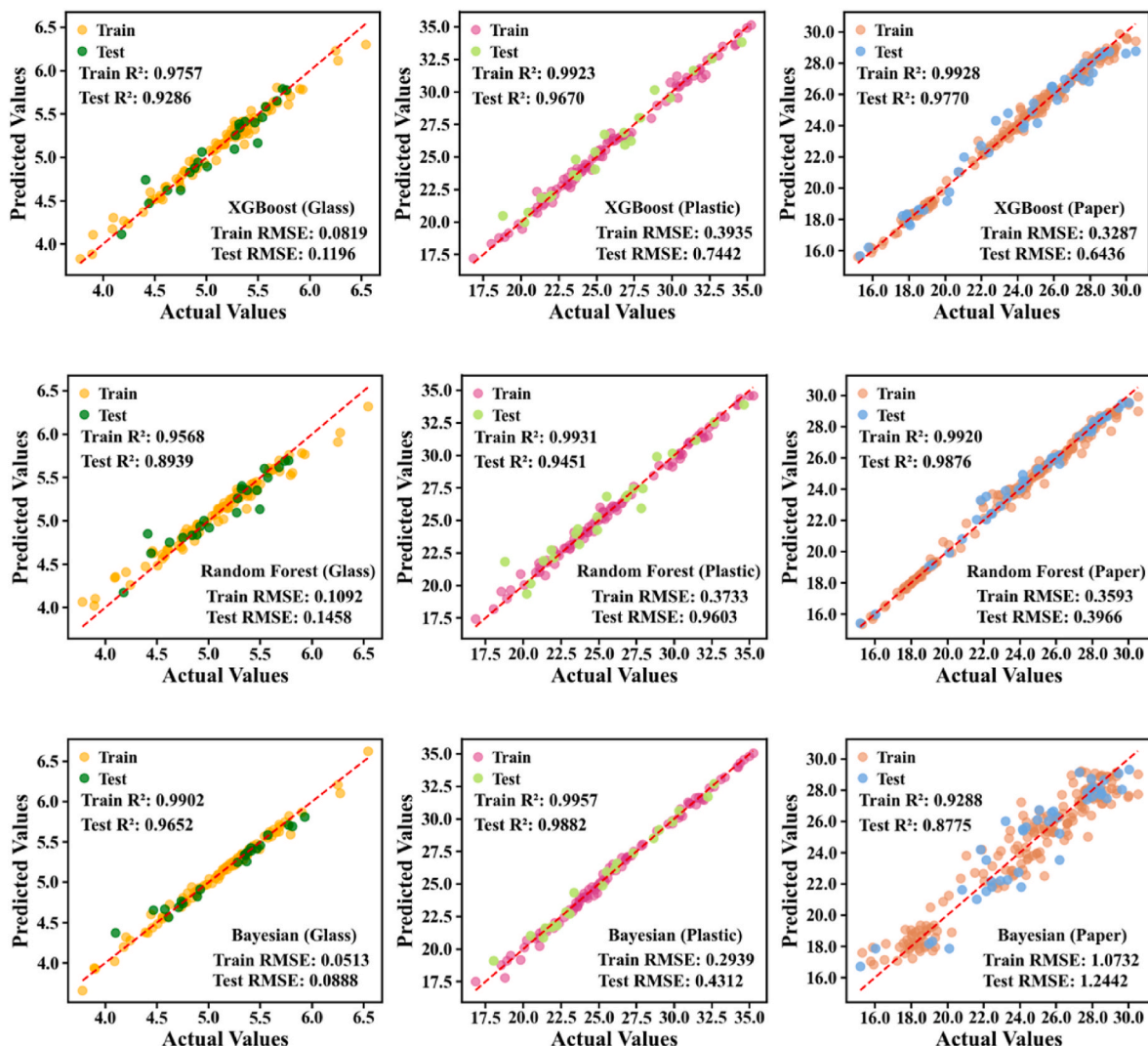


Fig. 5. Observed and predicted monthly municipal life-source recyclable generation using different machine-learning models.

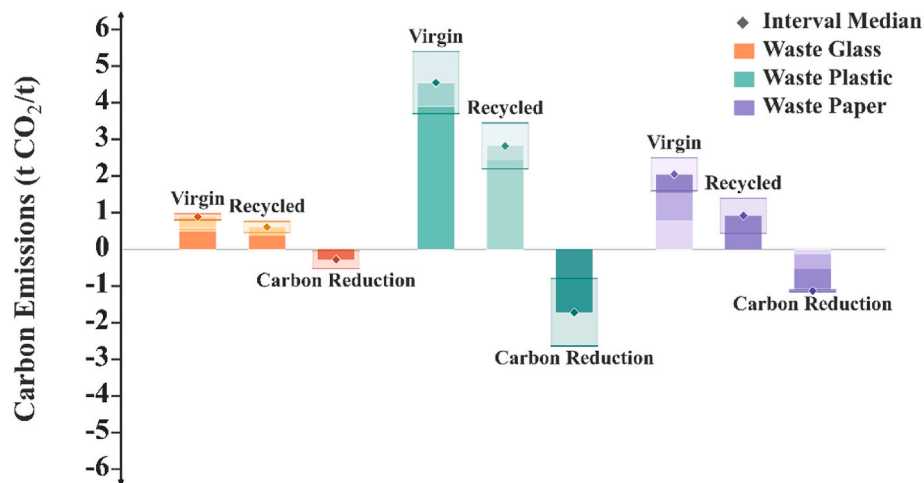


Fig. 6. Carbon-reduction potential of recycling pathways for glass, plastics, and paper under different scenarios.

routes, plastic recycling routes, and paper treatment routes. In the recycling scenario, a 100% recycling rate was assumed as a maximum resource-recovery potential scenario for all three waste categories, and emission coefficients were determined from published studies. Therefore, the estimated carbon-reduction benefits represent theoretical maximum potentials under complete recovery conditions rather than currently achievable outcomes. Specifically, CO₂ emissions from virgin-glass production ranged from 0.802 to 0.975 tons CO₂ per ton, whereas those from recycled glass ranged from 0.456 to 0.765 tons CO₂ per ton (Hu et al., 2018; Zhang, Q. et al., 2022). Recycling one ton of plastic instead of producing virgin plastic can reduce 1.1–3.0 tons of carbon dioxide equivalent emissions, while recycling one ton of paper reduces 1.10–1.18 tons CO₂, compared with 1.60–2.50 tons CO₂ from virgin-paper production, representing an approximate 50% reduction.

According to the simulation results, the carbon-reduction potential of household-source waste glass recycling ranged from 29,900 to 171,400 tons, with an average of 97,600 tons and a standard deviation of 29,100 tons; within the 95% CI, the reduction potential was 44,700–150,900 tons. For waste plastics, the range was 913,300–3,128,300 tons, with an average of 1,979,700 tons (SD = 37,100 tons) and a 95% CI of 1,276,200–2,689,100 tons. For waste paper, the reduction potential ranged from 1,212,100 to 1,287,600 tons, averaging 1,249,700 tons (SD = 12,400 tons) with a 95% CI of 1,225,800–1,287,600 tons.

The higher carbon-reduction potential of plastics and paper can be attributed to the relatively high emission intensity of virgin material production and the substantial substitution effect of recycling. In contrast, the carbon benefit of glass recycling is more sensitive to transport distance and processing efficiency because of its lower unit value and higher logistics burden.

After quantifying the carbon-reduction potential, the economic performance of the recycling pathways was further evaluated. Fig. 8 compares the unit economic value ranges of virgin production and recycling pathways for waste glass, waste plastics, and waste paper, providing a direct comparison of the cost differences among the three recyclable categories.

Furthermore, 50,000 Monte Carlo simulations were applied to estimate the cumulative probability distributions of economic benefits derived from the differences between the virgin and recycling pathways (Fig. 10). The estimated range of economic benefits for household-source waste glass was −4.6 to 28 million USD, with an average of 11.7 million USD (SD = 4.6 million USD) and a 95% CI of 2.5–20.7 million USD. For waste plastics, the range was 322–618 million USD, with an average of 466 million USD (SD = 61 million USD) and a 95% CI of 357–576 million USD. For waste paper, the estimated range was

1.142–1.315 billion USD, with an average of 1.227 billion USD (SD = 25 million USD) and a 95% CI of 1.179–1.275 billion USD.

Similarly, when extending the assessment from household-source generation to municipal life-source recyclable potential, The economic benefit distribution corresponding to the city's annual generation of municipal life-source waste glass ranges from −11.9 to 72.7 million USD, with an average cost reduction of 30.3 million USD and a standard deviation of 11.3 million USD. The coefficients of variation for the two simulation groups are 39% and 37%, respectively, indicating certain fluctuations in the economic benefits but an overall stable trend. For waste plastics, the economic benefit ranges from 1.077 to 1.529 billion USD, with an average cost reduction of 1.303 billion USD and a standard deviation of 103 million USD; the corresponding coefficients of variation are 13.1% and 7.9%, suggesting moderate variability yet overall stability.

The probability distributions obtained from Monte Carlo simulations capture the combined uncertainty associated with recyclable generation estimates and economic parameters. These economic benefits should therefore be interpreted as potential values under the assumed maximum resource-recovery potential scenario rather than current achievable outcomes. In practical applications, the realized economic performance may vary with collection efficiency, sorting performance, processing costs, and market conditions.

Waste paper shows a narrower range of 3.237 to 3.677 billion USD, with an average cost reduction of 3.459 billion USD and a standard deviation of 68 million USD; the coefficients of variation are 2.03% and 1.96%, indicating minimal volatility and high stability. The cumulative probability distribution results demonstrate that all three recyclable categories yield positive economic benefits in the vast majority of simulated scenarios. The probability of negative benefits for waste glass is less than 1% (0.62%), while waste plastics and waste paper show entirely positive outcomes across all simulations, indicating generally positive economic outcomes under the assumed parameter ranges.

These results suggest that environmental benefits alone are insufficient to determine recycling priority. Materials with stable market demand and higher substitution value, such as plastics and paper, are more likely to generate robust co-benefits, whereas glass recycling may require targeted incentives or localized treatment systems to remain economically viable.

The observed differences among the three recyclable categories indicate that the environmental–economic benefits of household-source recycling are highly material-dependent. Waste plastics and waste paper showed more stable co-benefits because their recycling pathways can avoid carbon-intensive virgin material production while maintaining relatively stable material substitution value. In Guangzhou, the

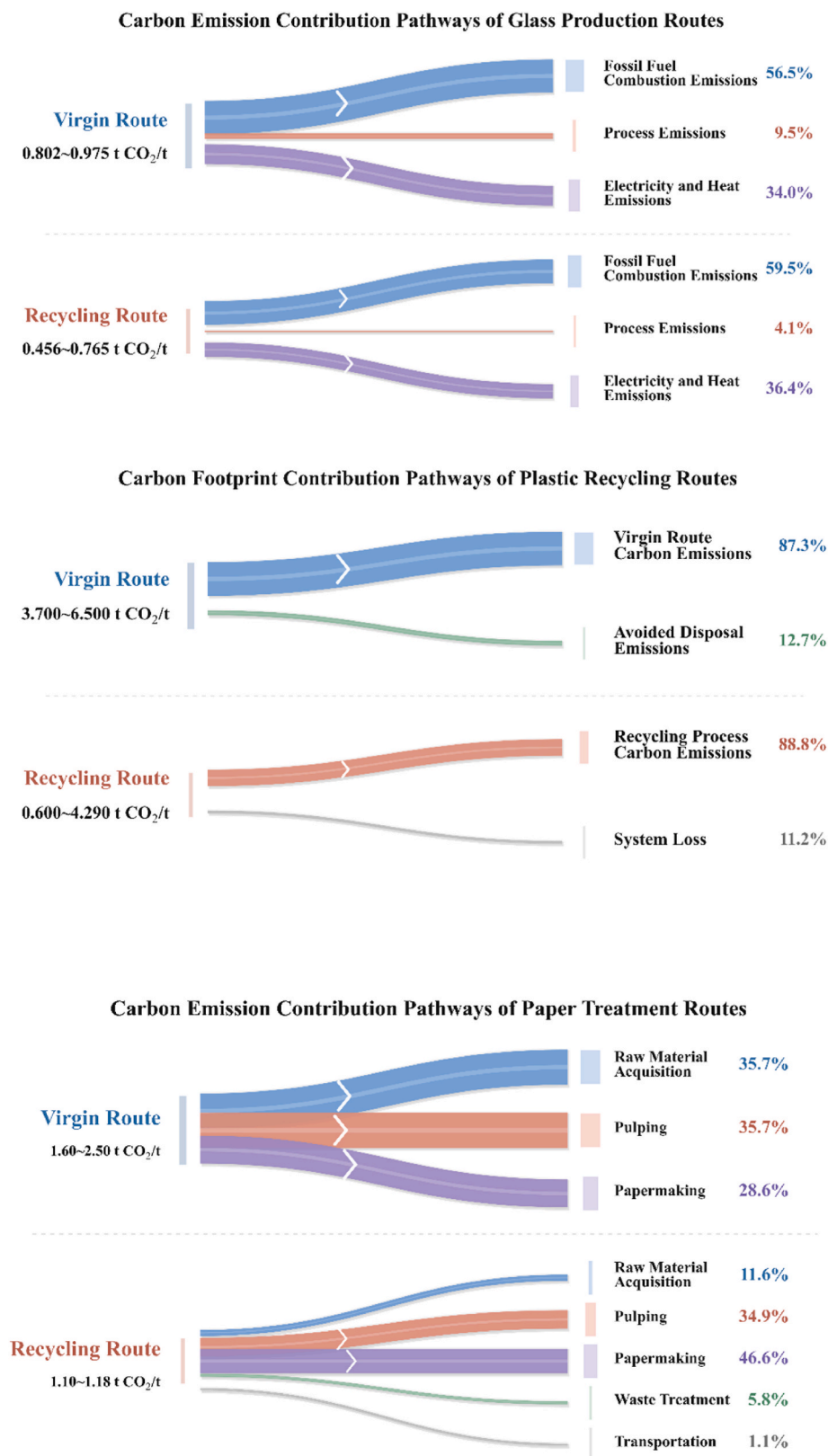


Fig. 7. Recycling pathway analysis and material flow structure for municipal solid waste management a) glass production routes, b) plastic recycling routes, and c) paper treatment routes.

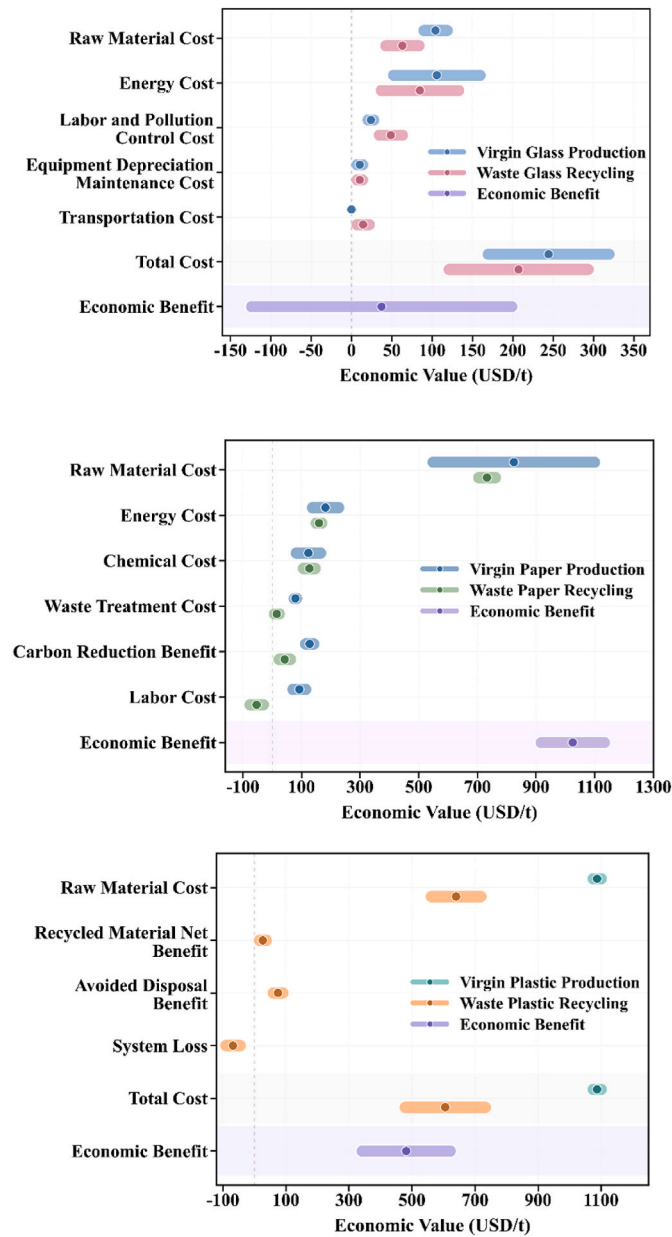


Fig. 8. Economic benefit comparison between virgin material production and recycling pathways for glass, plastics, and paper.

continuous generation of plastic packaging and paper products from household consumption, e-commerce, and commercial activities further supports stable recycling flows, enabling relatively robust carbon-reduction and economic benefits when source separation and downstream utilization are ensured.

In contrast, waste-glass recycling was more sensitive to market and operational conditions. Although glass recycling can reduce emissions by decreasing the demand for virgin raw materials and melting energy, its low unit value and high density make its benefits more dependent on transport distance, collection efficiency, and processing cost. In a large city such as Guangzhou, dispersed collection points, sorting facilities, and recycling plants may increase transportation costs and energy consumption, thereby weakening the overall environmental and economic gains.

These results suggest that differentiated recycling strategies should be adopted for household-source recyclables. For waste plastics and waste paper, priority should be given to improving source separation, reducing contamination, enhancing collection quality, and

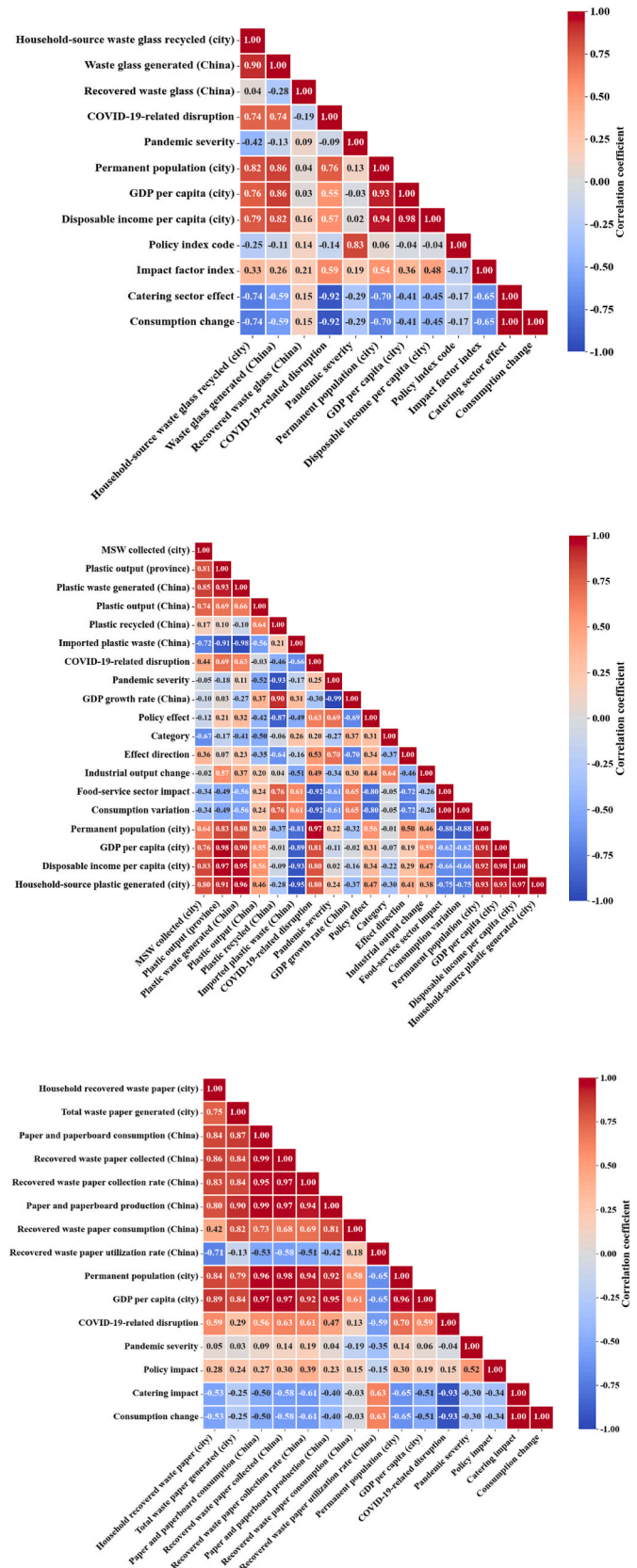


Fig. 9. Correlation analysis of key socioeconomic and structural variables influencing municipal life-source recyclable generation.

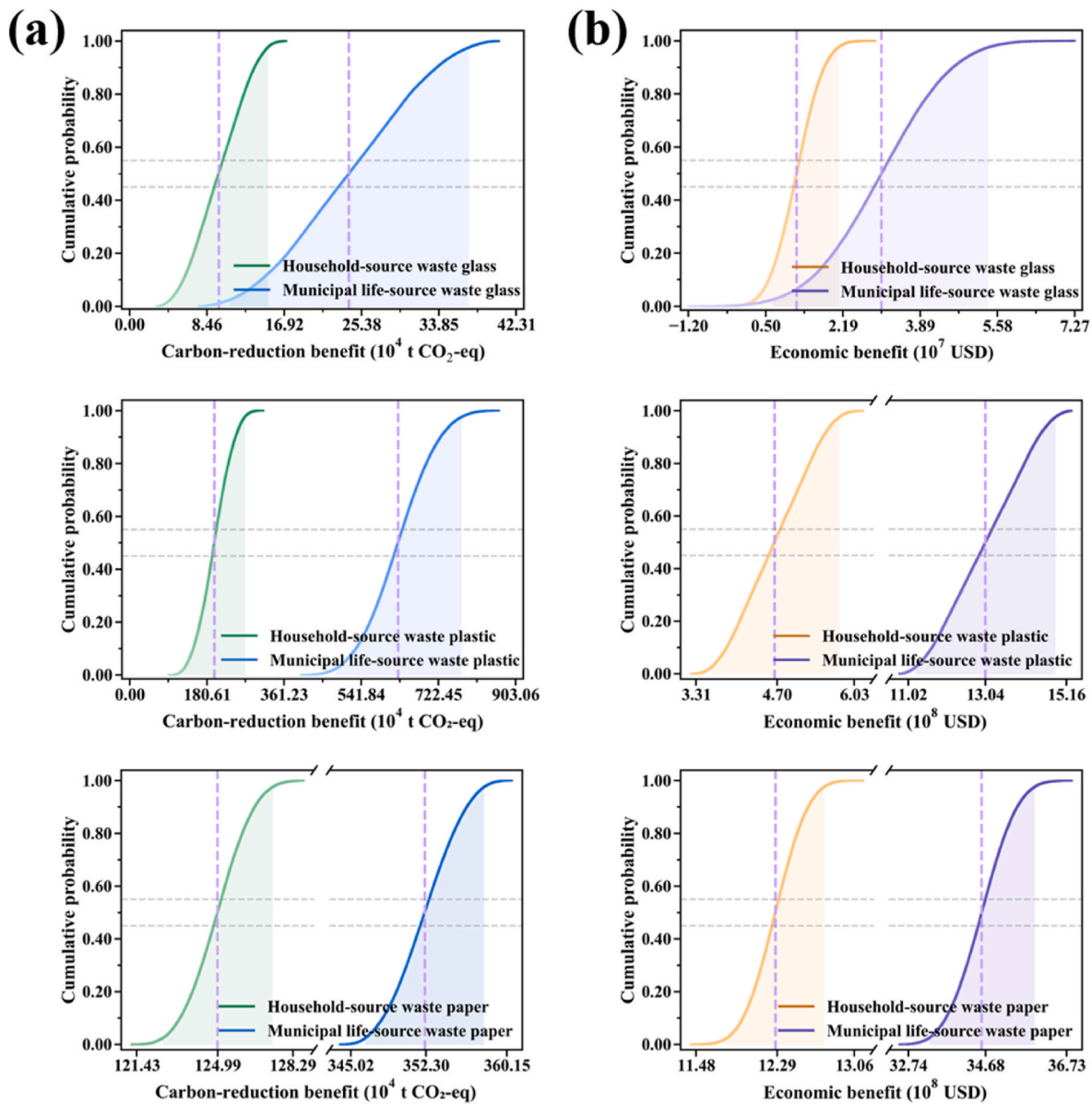


Fig. 10. Cumulative distribution functions (CDFs) of carbon-reduction potential and economic benefits for household-source recyclables and municipal life-source recyclables. Based on 50,000 Monte Carlo simulations.

strengthening downstream utilization. For waste glass, management should focus on reducing system costs through localized recycling networks, optimized transport routes, centralized collection points, improved sorting quality, and targeted incentives for low-value recyclables. Such material-specific strategies can better maximize the combined carbon-reduction and economic benefits of recyclable-waste management in Guangzhou.

3.3. Prediction of the growth of household-source recyclable waste

In this study, the main influencing factors and their corresponding intensities for predicting the city's waste-glass generation are shown in Table 3. The growth rate of waste-glass generation is primarily affected by population growth rate, government policies, and GDP growth rate. In constructing the prediction model based on Monte Carlo simulation, weights of 0.45, 0.45, and 0.10 were assigned to population growth, GDP growth, and policy factors, respectively, with appropriate random disturbances introduced to enhance model robustness. Between 2025

Table 3

Prediction of total municipal life-source recyclable generation and uncertainty for waste glass, plastics, and paper using different machine-learning models.

Model	Predicted Generation of Waste Glass (10^4 tons)	Standard Deviation (10^4 tons)	Predicted Generation of Waste Plastics (10^4 tons)	Standard Deviation (10^4 tons)	Predicted Generation of Waste Paper (10^4 tons)	Standard Deviation (10^4 tons)
XGBoost	61.47	1.62	310.00	15.48	310.96	5.73
Random Forest	61.01	1.70	312.33	8.82	319.46	4.24
Bayesian	61.45	8.11	327.20	13.65	335.60	25.93

and 2030, the city's population growth rate is expected to remain between 0.4% and 0.6% (Xie et al., 2016); from 2031 to 2035, as population aging intensifies and nearby urban development attracts migration, the growth rate is projected to slow to 0.2%–0.3% (Dai et al., 2022; Zhang et al., 2023). Meanwhile, the city's annual GDP growth rate follows the national average of 4.5%–5%, with an additional $\pm 1\%$ uncertainty range to account for possible policy adjustments affecting waste-glass generation (Al-Thaqeb and Algharabali, 2019; Chen et al., 2023). The data and parameters used in the prediction model are summarized in Table S8.

Through 50,000 Monte Carlo simulations, the probability distribution of future household-source recyclable waste generation within the 95% confidence interval was obtained, allowing projection of its long-term trend in the city. To visually illustrate the simulation process, 8000 random samples were extracted for visualization analysis. As shown in Fig. 11a, the simulation results indicate that by 2033, the annual generation of household-source recyclable wastes, including glass, plastics, and paper, in the city is expected to reach approximately 296,000 tons, 1,152,700 tons, and 1,298,300 tons, respectively.

Using household-source recyclable waste generation data, Monte Carlo simulations were conducted to project future trends in both carbon-reduction and economic benefits, with the results presented in Fig. 11b and c. Within the 95% confidence interval, the probability distribution of carbon-reduction potential for the years 2025–2035 was obtained. To more intuitively illustrate the simulation process, 8000 random samples were extracted from the 50,000 simulation runs for visualization analysis. As shown in the results, by 2033, the carbon-reduction potential from recycling household-source waste glass, plastics, and paper is projected to reach 116,600 tons, 2,363,000 tons, and 1,490,600 tons, respectively. Within the 95% confidence interval for 2025, the estimated economic benefit ranges of resource utilization for

the three recyclables are 17.9–83.2 million USD, 424–700 million USD, and 1.326–1.609 billion USD, respectively. During the simulations, variations were observed due to factors such as technological progress, labor costs, and resource substitution efficiency. Nevertheless, the overall trends remain clear, demonstrating that the recycling of these three waste categories contributes significantly and consistently to both carbon reduction and economic performance over the long term.

3.4. Policy implications

The findings suggest that recyclable-waste accounting in megacities should explicitly distinguish between household-source and municipal life-source recyclable flows. The substantial discrepancy between household-source observations and municipal life-source estimates indicates that accounting systems relying only on household surveys or formal collection records may underestimate the total recyclable resource potential. Integrating household-level measurements, multi-source socioeconomic indicators, and machine-learning-based city-scale prediction can therefore provide a more complete basis for urban recyclable-waste accounting, particularly when informal collection, direct reuse, and other unrecorded flows are considered.

The material-specific results further indicate that recycling strategies should be differentiated by waste category. Waste plastics and paper showed relatively stable carbon-reduction and economic co-benefits, supporting their prioritization in source separation, collection-quality improvement, and downstream recycling-capacity development. In contrast, waste glass was more economically sensitive because its recycling performance is strongly affected by market prices, transport distance, collection efficiency, and processing costs. For glass recycling, management efforts should therefore focus on localized collection networks, optimized transport routes, improved sorting quality, and

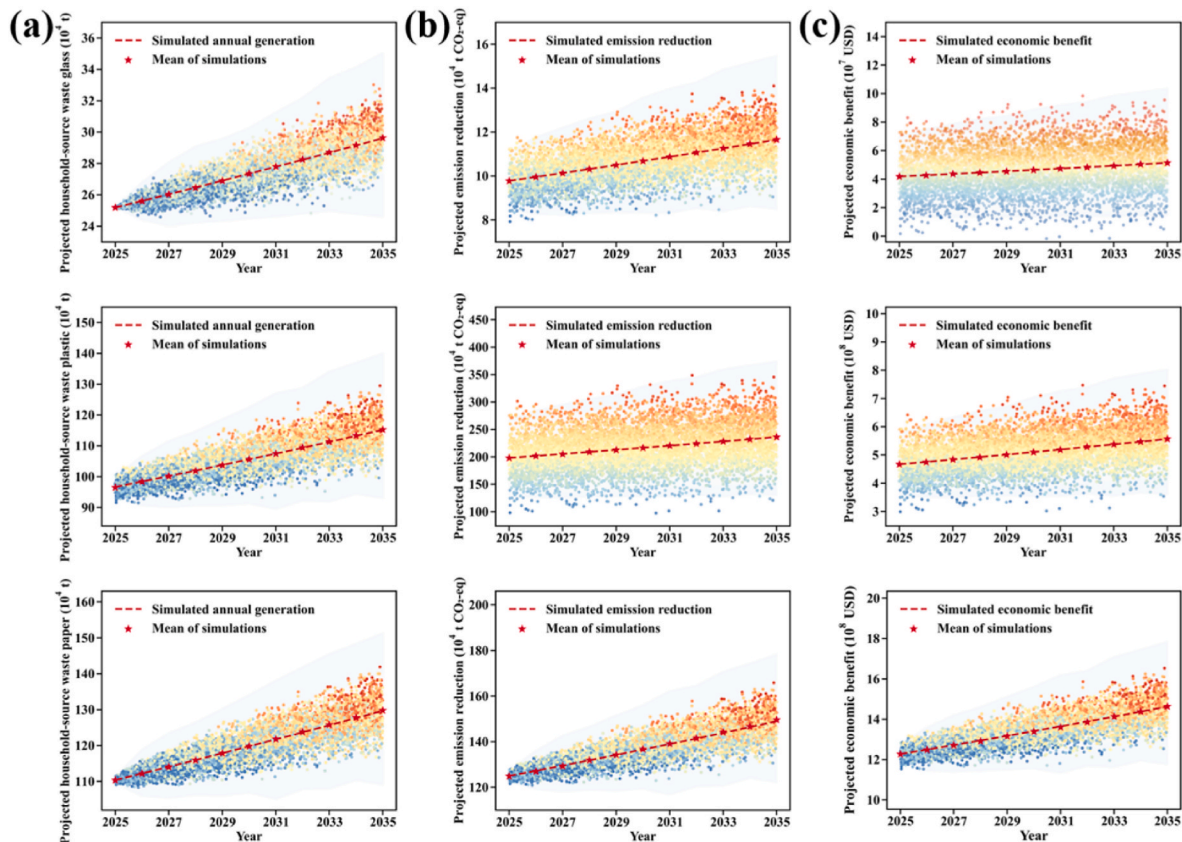


Fig. 11. Projected results of household-source waste glass, waste plastics, and waste paper in a city in China from 2025 to 2035: a) annual generation, b) annual carbon emission reduction from recycling, and c) annual economic benefits from recycling, based on 50,000 Monte Carlo simulations.

targeted incentives for low-value recyclables. The potential impacts on different stakeholders are further summarized in Table S8 in the Supplementary Information.

To support decision-making, a management prioritization matrix was developed based on carbon-reduction potential and economic performance/robustness (Fig. 12). Waste plastics and paper were positioned as priority materials because of their more stable environmental-economic co-benefits, whereas waste glass was classified as environmentally beneficial but economically sensitive, indicating a stronger dependence on system optimization and policy support. The stakeholder-level implications are summarized in Table S9. In addition, the projected increase in future recyclable-waste generation and recycling benefits highlights the need for a dynamic monitoring framework that regularly updates recyclable generation, emission-reduction potential, and economic performance indicators to support adaptive low-carbon waste management.

Beyond the Guangzhou case, the proposed framework provides a transferable approach for urban recyclable resource assessment. Its core components, including recyclable quantification, uncertainty analysis, machine-learning prediction, and environmental-economic assessment, are generally applicable, whereas local calibration of socioeconomic variables, policy-related indicators, recycling pathways, and market parameters is required to reflect regional differences in waste management systems and development conditions.

4. Conclusion

This study develops an integrated dual-scale framework to evaluate recyclable waste resource potential and its environmental-economic benefits in a Chinese megacity by combining household surveys, Monte Carlo simulation, machine-learning prediction, and scenario-based assessment. The framework explicitly distinguishes between household-source and municipal life-source recyclable waste, enabling a more comprehensive understanding of urban recyclable material flows across different spatial and functional scales.

Household-source generation of waste glass, plastics, and paper was estimated at 251,800, 966,500, and 1,103,500 tons, respectively, whereas the corresponding municipal life-source estimates reached 614,760, 3,100,000, and 3,109,600 tons, representing 2.44-, 3.21-, and 2.82-fold higher values. These differences reflect the broader accounting

boundary of municipal life-source recyclables rather than underestimation of an identical waste stream by household-level measurements. The two scales therefore provide complementary information on residential generation characteristics and broader city-scale recyclable resource potential.

Material-specific analyses further reveal pronounced heterogeneity in environmental and economic outcomes, with plastics and paper showing relatively stable co-benefits, while glass exhibits higher sensitivity to system efficiency and market conditions. The estimated environmental and economic benefits further demonstrate the resource-recovery potential of recyclable materials under the assumed recycling scenario.

From a methodological perspective, the integration of probabilistic simulation and machine-learning models provides a robust approach for capturing both data uncertainty and cross-scale prediction complexity in urban waste systems. This dual-layer framework improves the reliability of recyclable waste estimation and offers a transferable analytical tool for other rapidly urbanizing regions.

Overall, this study highlights the importance of dual-scale accounting in urban recyclable waste management and provides evidence-based support for optimizing material-specific, and low-carbon recycling strategies in megacities.

Future work could extend the current framework by incorporating additional types of low-value recyclables, applying it to other urban regions with locally calibrated parameters, refining temporal dynamics through longer-term monitoring, and improving the validation of future scenario projections through enhanced parameter calibration and real-world data integration.

CRediT authorship contribution statement

Jinfeng Tang: Writing – original draft, Supervision, Resources, Funding acquisition, Conceptualization. **Jiajun Lin:** Writing – original draft, Methodology, Data curation. **Minhua Su:** Writing – review & editing. **Yun Zhu:** Writing – review & editing, Data curation. **Biming Chen:** Writing – review & editing. **Benhua Liao:** Writing – review & editing. **Binglan Wu:** Methodology, Formal analysis, Data curation. **Kaimin Shih:** Writing – review & editing, Methodology. **Yongjun Wei:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Hongguo Zhang:** Writing – review & editing. **Junhua Xu:** Writing

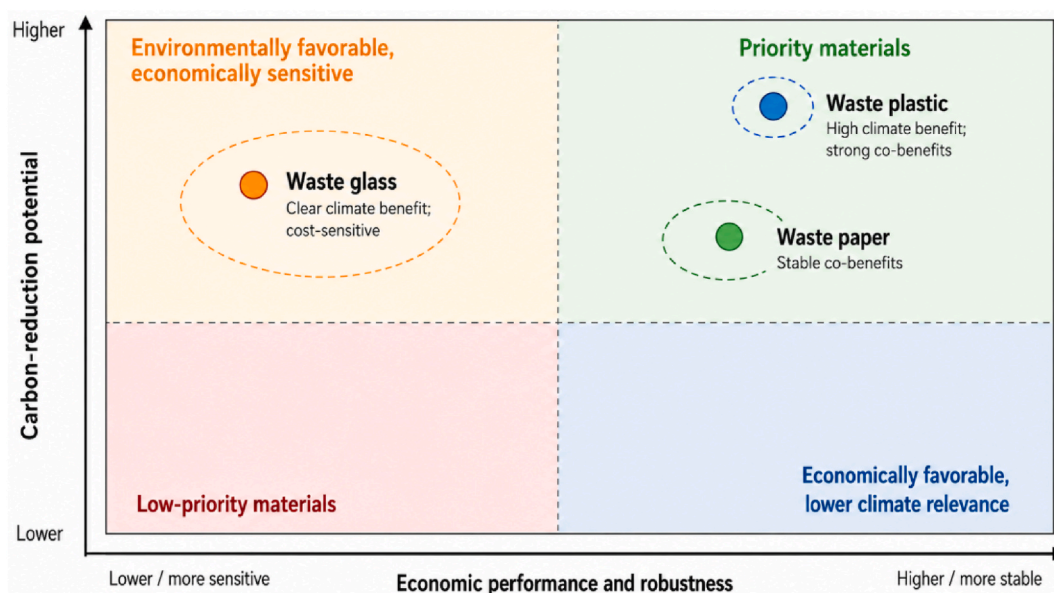


Fig. 12. Management prioritization matrix for household-source recyclables based on carbon-reduction potential and economic performance/robustness. The classification is derived from Monte Carlo simulation results and reflects the environmental-economic trade-offs and uncertainty characteristics of different materials.

– review & editing, Methodology.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to polish the English language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2026.149604>.

Data availability

Data will be made available on request.

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