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Sharing tableware reduces waste generation, emissions and water consumption in China's takeaway packaging waste dilemma

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China has a rapidly growing online food delivery and takeaway market, serving 406 million customers with 10.0 billion orders and generating 323 kilotonnes of tableware and packaging waste in 2018. Here we use a top-down approach with city-level takeaway order data to explore the packaging waste and life-cycle environmental impacts of the takeaway industry in China. The ten most wasteful cities, with just 7% of the population, in terms of per capita waste generation, were responsible for 30% of the country's takeaway waste, 27–34% of the country's pollutant emissions and 30% of the country's water consumption. We defined one paper substitution and two sharing tableware scenarios to simulate the environmental mitigation potentials. The results of the scenario simulations show that sharing tableware could reduce waste generation by up to 92%, and environmental emissions and water consumption by more than two-thirds. Such a mechanism provides a potential solution to address the food packaging waste dilemma and a new strategy for promoting sustainable and zero-waste lifestyles.

The digital revolution and changing lifestyles are reshaping the takeaway industry[1,2]. In China, online food delivery platforms such as Meituan, Ele.me and Baidu are undergoing rapid development, and traditional food shopping habits are changing with advances in e-commerce and mobile terminal technology[3,4]. It is estimated that users of online takeaway platforms in China increased in number from 60 million in 2011 to 416 million in 2019[5]. China's online food delivery and takeaway market value has experienced an estimated increase from 22 billion yuan in 2011 to 285 billion yuan in 2019[5], and the proportion of online takeaway turnover in the total catering industry in China increased from 1.4% in 2015 to 10.6% in 2018[6].

The negative impacts of the production and disposal of single-use plastic packaging on the environment and human health are growing global concerns[7–9], and in China, the 20 million takeaway orders placed per day across the three online food delivery platforms are associated with the use of 7.3 billion single-use plastic tableware sets per year[10]. China is now the world's largest plastic and waste producer, generating 60.4 million tonnes (Mt) of plastic products in 2018[11] and an estimated 553 kilotonnes (kt) of municipal solid waste (MSW) per day[12]. Packaging accounts for one-third of MSW.

A number of initiatives in China have sought new solutions for MSW management and plastic reduction, including the MSW sorting implementation plan jointly issued by the National Development and Reform Commission and the Ministry of Housing and Urban-Rural Development in March 2017[13], the 'zero-waste city' pilot programme by the General Office of the State Council in January 2019[14], and a nation-wide single-use plastic ban by the National Development and Reform Commission and the Ministry of Ecological Environment in January 2020[15]. In terms of the priority areas of plastic pollution such as from e-commerce and the takeaway industry, the Shanghai Association of Food Contact Materials has, for example, released three nonbinding food packaging standards to encourage the replacement of plastic food containers and bags with paper bowls and bags, and biodegradable sacks[16–18]. The standards were implemented on a trial basis by three online food delivery platforms in three districts of Shanghai from June 2018[19]. Shanghai was the first pilot city to implement the national MSW sorting policy, and the first mandatory regulation on domestic waste management in China came into force in Shanghai on 1 July 2019; it stated that restaurant and food delivery businesses could not provide single-use chopsticks and cutlery if not requested by consumers[20].

In terms of sustainable management strategies, a number of studies have focused on the environmental impacts of food tableware or packaging (for example, containers[21–28], cutlery[28–30] and bags[28,31,32]) with different materials (for example, petroleum-based polymers[21–26,30–33] and bio-based polymers[21,24,27,29,30,32,34,35]) and life-cycle processes. For example, within its lifespan, a Tupperware reusable food saver was shown to balance out the life-cycle impacts of

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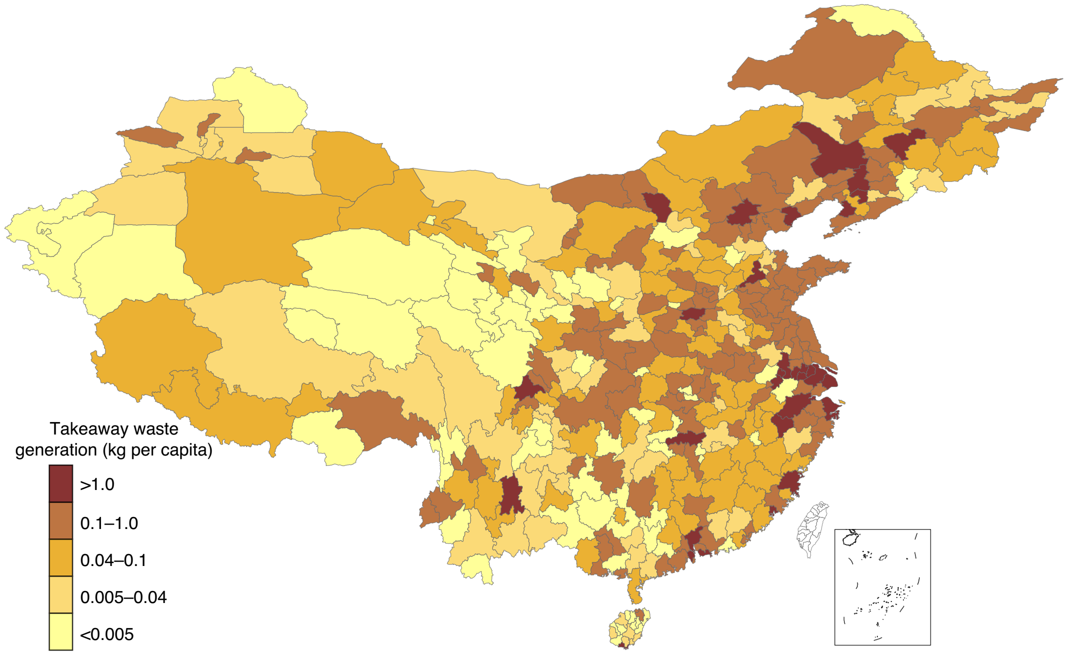

Fig. 1 | Takeaway packaging waste generated in 353 Chinese cities, 2018. The colours show the annual per capita waste generated by cities, with darker regions having higher waste. The takeaway packaging wastes are estimated in a top-down approach that downscales the national packaging consumption to the city level with takeaway orders collected from the Meituan online food delivery platform. Takeaway waste generated in Chinese cities varies notably; there is no takeaway restaurant information for the Shennongjia region (in Hubei province), Tongchuan (in Shannxi province), Gannan Tibetan Autonomous Prefecture (in Gansu province), Tibetan Autonomous Prefecture of Guoluo, Huangnan, Hainan and Yushu (in Qinghai province), Guyuan (in Ningxia province) and Atux (in Xinjiang province).

single-use plastic takeaway food containers made from aluminium or extruded polystyrene[26]. When life-cycle energy use and environmental emissions were compared between one-way and returnable food packaging systems in the European context, reusable packaging systems offered potential environmental and economic benefits over single-trip solutions[36,37]. Circular solutions associated with innovative reuse models, such as reusable packaging, can be effective alternatives in minimizing the negative externalities of plastic packaging[38,39].

As the sharing economy has the potential to promote shifts in collective consumption behaviour[40], sharing tableware may effectively decrease single-use plastic packaging and enhance the sustainability of the takeaway industry. Here we quantify the takeaway packaging waste and seven environmental indicators of China's takeaway industry. We use a top-down approach that divides the national packaging consumption into 353 cities on the basis of city-level takeaway order data collected from Meituan, the largest Chinese online food delivery platform (http://waimai.meituan.com). Mitigation scenarios, such as paper substitution and tableware sharing, are compared with the baseline scenario, and we show that sharing tableware is a potential solution to reduce takeaway packaging waste and a new strategy for promoting sustainable and zero-waste lifestyles.

Results

Waste generated by online takeaway orders. The Chinese online food delivery and takeaway industry served 406 million customers with 10.0 billion orders[41], and generated 323 kt of tableware and packaging waste (218 kt plastic waste) in 2018 (Extended Data Fig. 1), which is equal to three-fifths of China's overall MSW generation per day, 13 days of MSW generation in Beijing and 1 month of MSW generation in Dongguan (a city in Guangdong province)[12]. The national average per capita takeaway waste generated is 0.24 kg per year, and that generated in cities is shown in Fig. 1. Wuxi (a city in Jiangsu province) has the largest per capita takeaway waste (1.46 kg per year), 6 times higher than the national average, and 5.12 million times higher than that of Diqing (a city in Yunnan province).

The ten most 'wasteful' cities (shown in Fig. 2) produce 30% (97.5 kt) of the country's takeaway waste. As the largest packaging producer (21.8 kt), Shanghai ranked seventh in per capita packaging waste (0.90 kg). Wuxi was the fifth packaging waste producer (9.6 kt) but contributed the largest per capita packaging waste (1.46 kg), indicating that people in Wuxi order more takeaway than those in other cities. Generally, cities on the east coast (for example, nine of the top ten cities) have a greater economy in terms of takeaways and produce the highest amount of waste per capita, followed by the cities in the central and western regions (for example, all of the bottom ten cities as ranked by waste generation in Fig. 2). Food containers, chopsticks and plastic bags make up 44%, 19% and 17% of the total takeaway waste, respectively.

Environmental impacts of online takeaway orders. China's online takeaway ordering produced 709 kt of CO_2, 2.0 kt of SO_2, 2.6 kt of NO_x, 485 t of fine particulate matter (particles of less than 2.5 μm in diameter; $PM_{2.5}$), 436 mg of dioxin and 2.8 kt of chemical oxygen demand (COD), and consumed 2.5 million m^3 of water in 2018. Single-use food containers, plastic bags and tissues have higher environmental impacts (85% on average) compared with other takeaway packaging. Food containers are the largest contributor to CO_2 (57% of the total CO_2), SO_2 (52%), NO_x (48%), $PM_{2.5}$ (48%) and dioxin (46%) emissions from takeaway packaging and are responsible for the greatest river water consumption (47%) from takeaway packaging. Plastic bags are the second-greatest contributor of emissions of CO_2 (25%), NO_x (18%), $PM_{2.5}$ (39%) and dioxin (17%). Napkins make up the largest share of COD emission (59%)

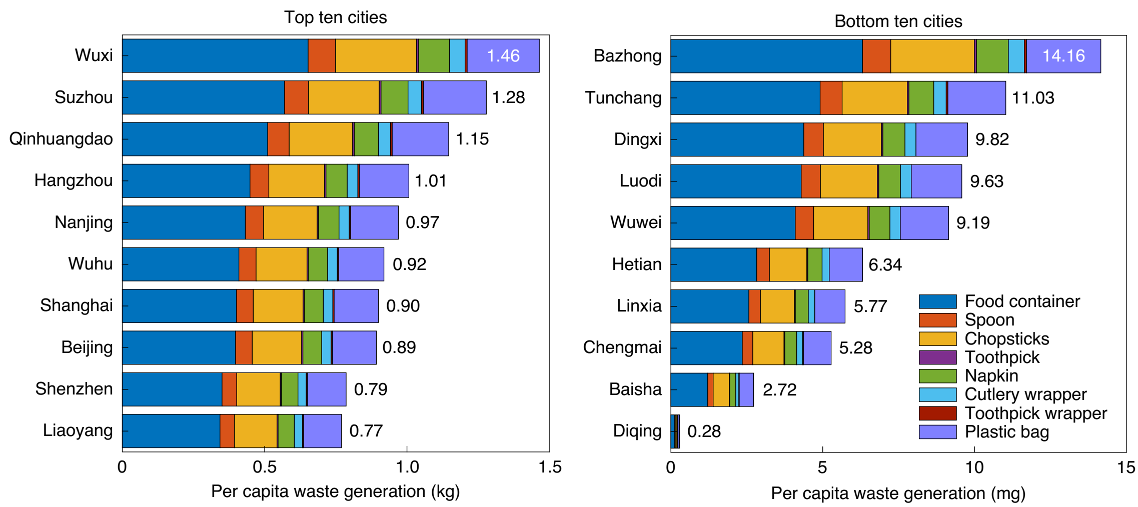

Fig. 2 | Top and bottom Chinese cities in per capita takeaway packaging waste. The cities are ranked by per capita takeaway packaging waste after dividing the city takeaway packaging waste by the population. The bar charts show the per capita takeaway packaging waste of the top (left) and bottom (right) ten cities, and the contribution of each tableware and packaging type is shown in a different colour.

Table 1 | Takeaway environmental impacts by tableware and packaging, and life cycle processes in China, 2018

Indicator (unit)	CO_2 (kt)	SO_2 (t)	NO_x (t)	$PM_{2.5}$ (t)	Dioxin (mg)	COD (t)	Water (10^3 m^3)
By tableware and packaging							
Food container	406.09	1,057.12	1,241.83	231.45	202.41	708.07	1,157.91
Spoon	62.33	166.47	165.96	10.88	22.44	37.65	141.92
Chopsticks	4.56	45.59	333.65	23.55	50.04	65.29	307.57
Toothpick	0.12	1.19	8.88	0.60	1.35	1.81	8.69
Napkin	24.93	354.89	267.49	21.80	55.43	1,627.69	493.13
Cutlery wrapper	35.13	62.08	93.39	7.26	17.97	22.38	98.53
Toothpick wrapper	1.58	6.60	13.56	0.35	14.27	19.64	71.26
Plastic bag	174.65	321.45	467.94	189.19	72.50	280.63	184.14
By life-cycle process							
Material production	417.07	1,339.84	1,009.60	392.19	81.31	2,281.58	1,053.17
Transportation	3.39	58.76	1,412.92	16.71	0.47	60.16	365.54
Tableware production	45.29	591.21	118.19	53.85	81.94	184.56	917.91
Incineration	243.14	23.09	50.26	21.94	268.86	85.83	119.65
Landfill	0.51	2.01	1.74	0.19	3.83	153.03	5.88
Total	709.39	2,015.39	2,592.71	484.88	436.42	2,763.15	2,463.16

The environmental impacts of the takeaway industry are the sum of the life-cycle phases of eight types of tableware and packaging. The environmental impact of each packaging type is estimated by multiplying the annual packaging consumption by the life-cycle emission factor. Six life-cycle phases including production of raw material ('Material production'), transportation of raw materials to production sites, production and packaging of tableware and packaging ('Tableware production'), distribution of tableware and packaging products to suppliers, takeaway delivery to consumers, utilization of tableware and final disposal ('Incineration' and 'Landfill') are considered, while the data for the transportation of raw materials for tableware production, tableware production for suppliers and takeaway delivery are aggregated into the 'Transportation' phase. There is no additional environmental impact in the tableware utilization phase under the baseline scenario.

and the second-largest share of SO_2 emission (18%) and water consumption (20%). The results for tableware and life-cycle processes are presented in Table 1. From a life-cycle process perspective, the production of raw material and tableware contributes more than four-fifths of the whole life-cycle environmental impacts (that is, 96% of SO_2, 92% of $PM_{2.5}$, 89% of COD and 80% of water consumption). Production of raw material is the major source of CO_2 emissions (59%), followed by incineration (34%). Incineration accounts for the largest dioxin emission (62%). Transportation contributes the least to environmental impacts (less than 13%, except for NO_x emission, which is 54%).

There are large regional differences in the environmental impacts of the takeaway industry in Chinese cities (see Supplementary Table 6 for each environmental impact). We find that relatively few cities are responsible for a disproportionately large share of the total emissions and water consumption. For example, the ten most 'wasteful' cities contribute 32% of the county's CO_2 emissions and 30% of the county's water consumption from takeaway packaging, but have just 7% of the population (pollutant emissions can be found in Supplementary Table 6). As the most developed regions in China, city clusters of the Beijing-Tianjin-Hebei region, the Yangtze River Delta and the Pearl River Delta, including approximately

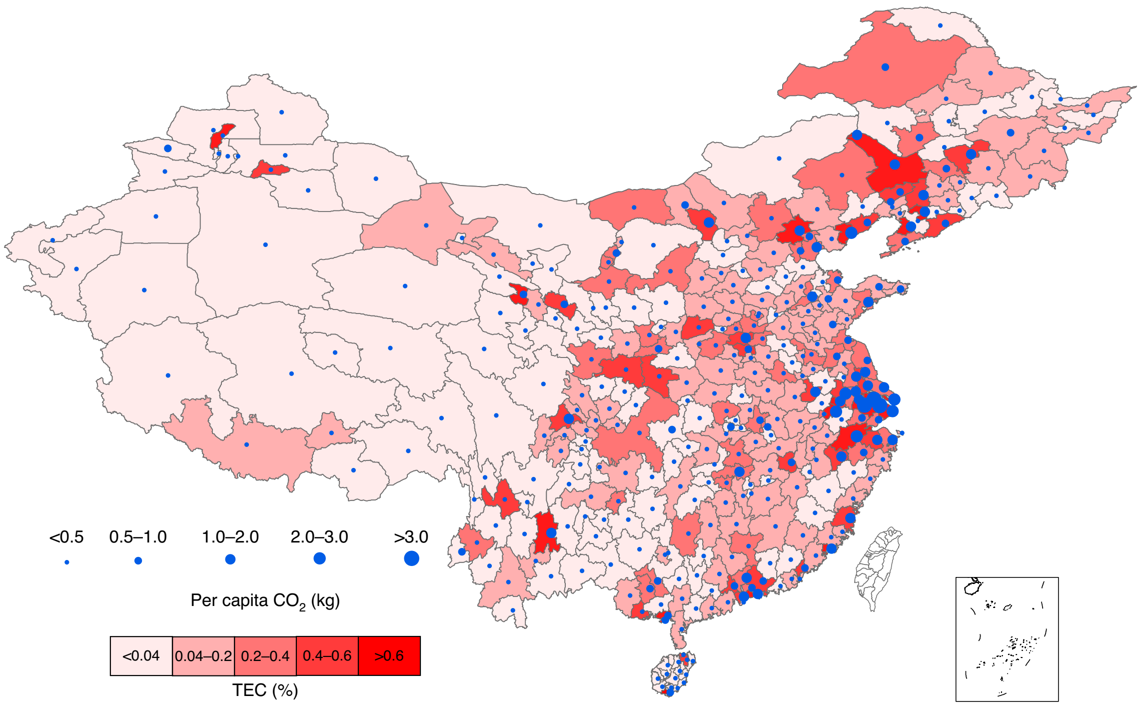

Fig. 3 | Life-cycle takeaway CO_2 emission and TEC of Chinese cities, 2018. The blue dots represent the takeaway CO_2 emission per capita of the cities. The larger the dots, the larger the per capita CO_2 emission estimated by dividing the life-cycle CO_2 emissions of eight takeaway packaging types by the population. The colours of the cities show their TEC, defined as the proportion spent on takeaway of the household expenses. The annual takeaway spending of the city is determined by multiplying the annual takeaway order volume by the associated sale price. Darker red colours represent higher proportions of income spent on takeaway. We examine the Pearson correlation coefficients between the TEC and per capita CO_2 emission in cities (0.817, $P = 0.000$). There are strong correlations between the variables at the 0.01 significance level (two-tailed), indicating that the per capita takeaway CO_2 emission is closely related to the TEC.

one-seventh of the country's cities, are responsible for 53% of the country's CO_2 emissions and 48% of the county's water consumption from takeaway packaging, and have 24% of the population. Rich and tourist cities have larger environmental impacts from takeaway orders than others (Extended Data Fig. 2). See Extended Data Fig. 2b of the top ten cities in per capita CO_2 emissions as an example. As popular tourist cities, Qinhuangdao in Hebei province (2.5 kg per capita), Kunming in Yunnan province (2.0 kg per capita) and Sanya in Hainan province (1.9 kg per capita) have large CO_2 emissions from takeaway packaging.

We define the takeaway Engel coefficient (TEC), as shown in Fig. 3, to further explore the city-level takeaway spending and lifestyle differences. A higher TEC (darker red in Fig. 3) indicates proportionately greater spending on takeout. We find that tourist and rich cities have larger TECs than others, indicating that their residents are willing to pay more on takeaway food. Among the top ten cities with high TECs, six are tourist cities, namely Liaoyang (in Liaoning province), Behai (in Guangxi province), Sanya (in Hainan province), Kelamayi (in Xinjiang province), Xiamen (in Fujian province) and Tongliao (in Inner Mongolia province). The remaining four cities (Wuxi and Suzhou in Jiangsu province, Wuhu in Anhui province and Shenzhen in Guangdong province) are rich, coastal cities. The less-developed cities in the western region (for example, Loudi in Hunan province and Wuwei in Gansu province) have lower TECs. The TEC of Wuxi is 0.88%, which is 5.2 times higher than the national average (0.17%) and 2,640 times higher than that of Loudi, and the takeaway CO_2 emission of Wuxi is 4.01 kg per capita, which is 8 times higher than the national average (0.52 kg per capita) and 236,239 times higher than that of Loudi. High-income cities in developed areas with high TECs contribute larger takeaway CO_2 emission than do low-income cities, and these large cities face greater environmental burdens.

Tableware sharing to mitigate impacts of online takeaway orders. With the fast development of a circular and sharing economy[40,42], paper alternatives and reusable tableware provide potential solutions to mitigate the environmental impact of the takeaway industry in China. To evaluate the mitigation potentials of different management strategies for the Chinese takeaway industry, we define three scenarios (see the Scenario design section, Extended Data Fig. 1 and Supplementary Table 1 for more details), a paper substitution scenario and two tableware sharing scenarios.

The paper substitution scenario involves a set of tableware that includes a polyethylene-coated kraft paper container; a kraft paper bag; and a single-use cutlery package, comprising a polypropylene spoon, a pair of wooden chopsticks, a wooden toothpick and its wrapper, a napkin and a biaxially oriented polypropylene chopstick wrapper.

The tableware sharing scenario involves a reusable and returnable tableware set that includes a silicone container (Partita); a reusable high-density polyethylene nonwoven bag; and a cutlery package (wrapped with a napkin), comprising a reusable silicone spoon, a pair of reusable wooden chopsticks, a recycled napkin and a wooden toothpick and its recycled wrapper. Two different take-back mechanisms are considered, namely a centralized take-back mechanism whereby all tableware is collected by courier and hand-washed in the restaurant separately, and a decentralized take-back mechanism that assumes all of the reusable tableware is returned to collection points by consumers and machine-washed in central cleaning stations.

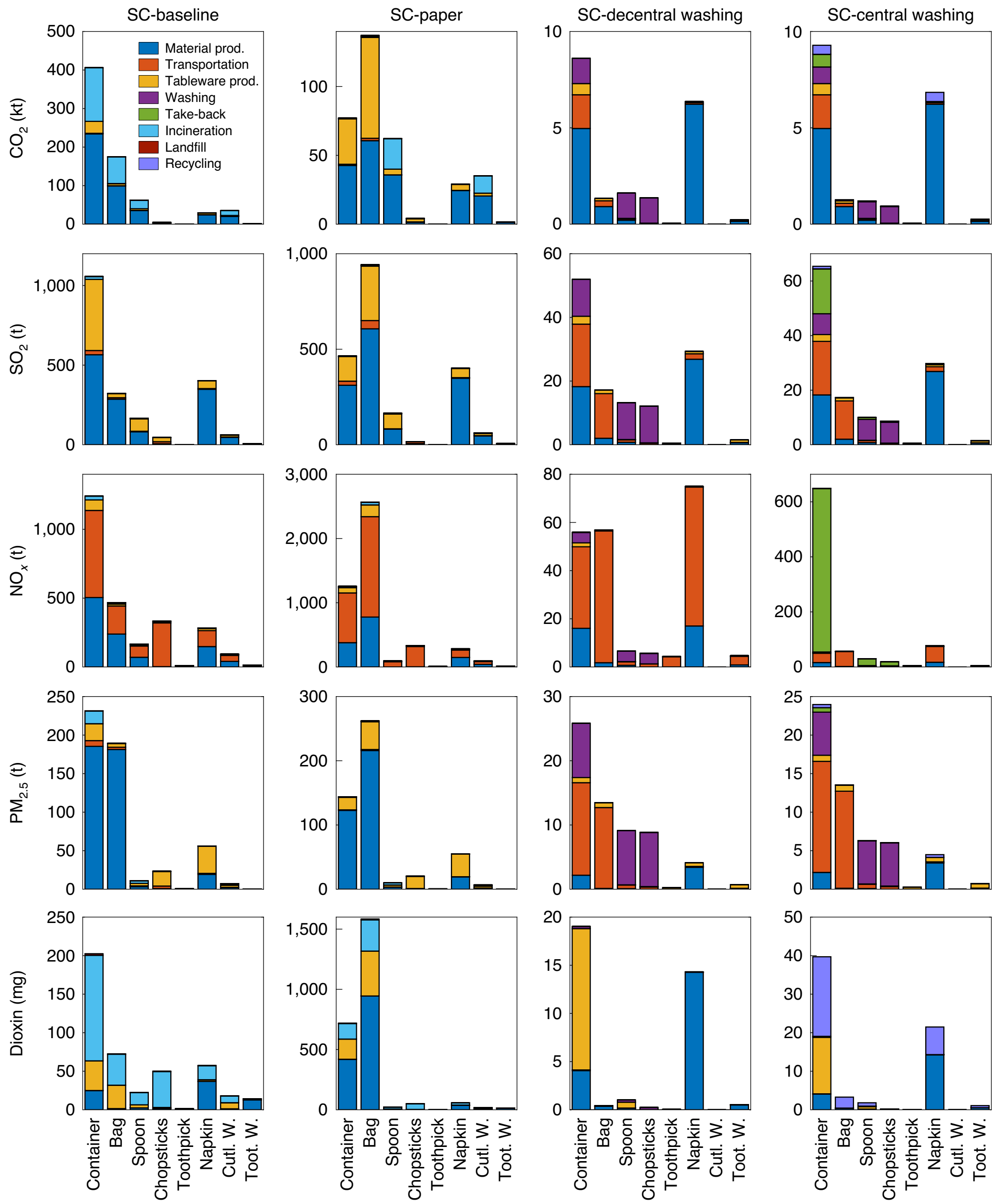

Fig. 4 | Life-cycle takeaway environmental impacts (air) by tableware and packaging type under different scenarios. Bar charts indicating the CO_2 and four air pollutant emissions by six life-cycle phases and eight tableware and packaging types under the baseline (SC-baseline), paper substitution (SC-paper) and two tableware sharing scenarios. 'SC-decentral washing' denotes sharing tableware collection with manual washing in restaurants. 'SC-central washing' represents the decentral collection of sharing tableware with machine washing. 'Material prod.' represents the production of raw material, and 'Tableware prod.' denotes the production of tableware and packaging. 'Transportation' represents material transport to tableware manufacturers, tableware transport to suppliers and the food delivery to consumers. 'Incineration' and 'Landfill' represent the end-of-life processes for single-use tableware and packaging, and 'Recycling' represents the final disposal for reusable items. 'Washing' and 'Take-back' belong to the utilization of sharing tableware phase, respectively indicating water, electricity and detergent consumption during the washing process, and transport from decentralized tableware collection points to central cleaning centres and transport back to restaurants. Cutl. W., cutlery wrapper; Toot. W., toothpick wrapper.

Figures 4 and 5 show the life-cycle environmental emissions and water consumption by tableware and process under different scenarios, and different scales are used side-by-side for the same indicator. The paper substitution measure can reduce plastic waste by 57% (183 kt) and CO_2 emissions by 49% (365 kt), but it creates an additional 493 kt of paper waste, corresponding to 1.5 times the waste generated in the baseline scenario. As pulp and paper production is one of the most energy-intensive manufacturing sectors[43], paper substitution produces 79% more NO_x, 465% more dioxin and 89% more COD emissions, and consumes an additional 41% of water.

Paper bags and paper food containers are the primary sources of CO_2 (62%), SO_2 (70%), NO_x (82%), $PM_{2.5}$ (87%), dioxin (93%) and COD (66%) emissions, and water consumption (68%). Dioxins are mainly by-products of industrial processes, especially chlorine bleaching of paper pulp, and production of raw material (for example,

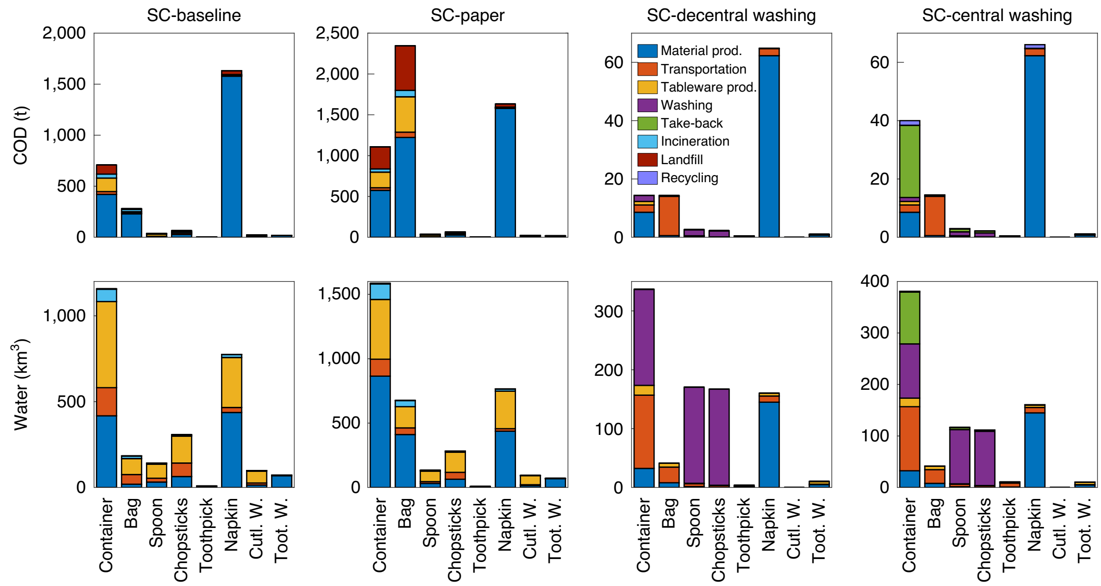

Fig. 5 | Life-cycle takeaway environmental impacts (water) by tableware and packaging type under different scenarios. Bar charts indicating COD emission and water consumption by six life-cycle phases and eight tableware and packaging types under the baseline (SC-baseline), paper substitution (SC-paper) and two tableware sharing scenarios. The abbreviations for the scenarios and life-cycle phases are the same as in Fig. 4.

kraft paper) is responsible for the largest share of the dioxin emissions (58%). Raw material production contributes the most to the COD emissions (66%), followed by landfill (17%) and tableware production (13%).

The results could be attributed to the fact that withstanding the same pressure and having the same volume, the paper bag has more mass, about seven times more than the plastic bag. Paper bag production consumes 1.1 times the energy and four times the amount of water, leads to 14 times the eutrophication of water bodies, and produces 2.7 times the solid waste it takes to make plastic bags[44]. For those areas without formal waste collection and recycling systems, paper substitution is not the optimal option for addressing the takeaway packaging waste dilemma.

Tableware sharing scenarios have stronger mitigation effects on environmental impacts, reducing takeaway waste by 92% (295 kt, including 217 kt of plastic waste, 63 kt of disposable chopsticks and 13 kt of paper waste) and environmental impacts by more than two-thirds (97% of CO_2, 93% of SO_2, 68% of NO_x, 89% of $PM_{2.5}$, 84% of dioxin, 95% of COD and 67% of water for decentralized take-back) compared with the baseline scenario. The use of recycled napkins can mitigate more than one-half of environmental impacts (that is, 73% of CO_2, 52% of SO_2, 17% of NO_x, 38% of $PM_{2.5}$, 61% of dioxin and 96% of COD for decentralized take-back) and 67% of water consumption compared with the use of virgin napkins.

The production of material and tableware generates the largest environmental emissions (CO_2, dioxin and COD), followed by transportation (including take-back logistics) and the washing phase. For SO_2, NO_x and $PM_{2.5}$ emissions and water consumption, transportation is the main contributor. The life-cycle water consumption of a reusable tableware set is 21 times higher than that of a one-way tableware set (Supplementary Table 9). The water consumption of reusable tableware is only 30% of the cumulative value for one-way tableware in a year period. There are similar tendencies for other indicators, indicating that reusable tableware has a resource-saving benefit and environmental mitigation potential.

The decentralized collection scenario has larger SO_2, NO_x and COD emissions than centralized take-back owing to the extra impacts of take-back logistics. Take-back transportation contributes 4% of CO_2 emissions, less than 16% of air pollutant emissions (SO_2, $PM_{2.5}$ and dioxin) and water consumption, and 21% of COD emissions, but contributes the largest NO_x emissions (75%). Compared with centralized collection with manual washing, the decentralized collection with machine washing can save another 31,617 kWh of electricity, 2,000 m^3 of water and 1.4 kt of detergent, corresponding to reducing by more than one-third the environmental impact of the washing process (that is, 34% of CO_2, SO_2, NO_x and $PM_{2.5}$, and 35% dioxin, COD and water).

Discussions and policy implications

To deal with the problem of takeaway packaging waste in China, policymakers need specific information on the environmental impacts of the takeaway industry. We developed a top-down approach to estimate the takeaway waste generation and the life-cycle environmental impacts in China with city-level meal ordering data from Meituan. The data for the potential environmental impacts of different management strategies indicate that tableware sharing is an effective and sustainable way to lessen the environmental impact of the takeaway industry.

The findings of the sensitivity analysis demonstrated that life-cycle inventory (LCI) datasets from different geographic regions have notable impacts on the results (Supplementary Table 7). The baseline scenario is less sensitive than the paper substitution scenario. The effects of the LCI datasets on the baseline results of CO_2, COD and water are within 10% of each other. SO_2, NO_x, $PM_{2.5}$ and dioxin emissions are more sensitive than other indicators. Transportation contributing to the largest effects of CO_2, NO_x, COD and dioxin emissions is more sensitive than other life-cycle phases. If the weights of the food container and the bag were increased by 5%, their environmental impacts would increase by 1% to 4% (Supplementary Table 8). Paper containers and bags are more sensitive than plastic ones for packaging weights. The shared tableware and packaging could balance out the CO_2, SO_2, NO_x, $PM_{2.5}$ and COD emissions of the same amount of single-use plastic packaging in the baseline scenario after being reused 14 times (39 times for water consumption and 91 times for dioxin emission, as shown in Supplementary Table 9).

Even for 90% and 75% return rates, shared tableware requires 20 reuses to offset the impact of the disposable item in the baseline and paper substitution scenarios (43 times for water consumption and 122 times for dioxin emission).

The sustainable model of sharing tableware needs to be established to achieve win–win outcomes among government, restaurants, food delivery platforms and consumers. Measures for the supervision and administration of takeaway food safety[45] and food safety operation specifications[46] came into force in the online takeaway services of China in 2018, and the government should propose incentives and punitive schemes for the adoption and safe use of sharing tableware. The online food delivery platforms should be responsible for the distribution and monitor the usage of shared items. The restaurants and the consumers could increase star ratings and receive subsidies by using and returning the reusables. Public education and guidance encourage consumers to make sustainability a key factor in using and returning sharing items. The sharing tableware should be used as a pilot study in cities that have large takeaway customer bases. With joint efforts and mutual cooperation, the sharing packaging mechanism can not only accelerate the transition to a zero-waste takeaway future, but also be promoted to the retail, catering and logistics industries to create a zero-waste society. By comparing the life-cycle environmental impacts of sharing takeaway packaging with those of single-use items, we hope that tableware sharing can serve as a feasible solution for reducing food delivery packaging waste, which many cities around the globe struggle with, and help integrated policymaking for the sustainable development of the takeaway industry.

There are uncertainties and limitations in this study. We made assumptions to simplify the type, material and size of tableware and packaging. The city-level meal ordering data were collected from the Meituan platform, and the possible asymmetries existing in the remaining takeaway market were not considered. The resource consumption during the washing process may be different among shared items; we calculated them as a tableware set owing to the data limitation. LCIs for seven environmental indicators were compiled, and impact category indicators were quantified to assess the effects of the takeaway industry on the environment and human health. We focused only on the environmental impacts of takeaway packaging, and food waste was excluded. A population's acceptance and human behavioural change under the sharing mechanism is a good point from which to explore the environmental impacts of food waste.

Methods

The life-cycle environmental impacts of China's takeaway industry were estimated under three scenarios (see the Scenario design section), while potential environmental mitigation strategies with different packaging materials and management mechanisms were explored. The system boundary and functional unit was production, packaging, transportation, utilization and disposal of annual tableware and packaging consumed in China's takeaway industry (Extended Data Fig. 3), and the production of machinery and infrastructure was excluded. As cutlery and napkins are habitually bundled with takeaway orders, each takeaway was assumed to be equipped with a set of tableware and packaging (see Extended Data Fig. 1 and Supplementary Table 1 for more details). Based on the life-cycle thinking method and ISO 14040/44 methodological guidelines[47,48], the annual environmental impact was calculated by multiplying the consumption of tableware and packaging by the corresponding emission factor (equation (1)).

$$\mathrm{EF}_{s,k} = \sum_{i=1}^{I} \sum_{j=1}^{J} \mathrm{AD}_{s,i} \times \mathrm{CF}_{s,k,i,j} \quad (1)$$

where $\mathrm{EF}_{k,s}$ represents the environmental emission and water resource consumption of environmental indicator *k* under scenario *s*; $\mathrm{AD}_{s,i}$ denotes the annual tableware or packaging *i* consumption related to takeaway order amount under scenario *s*; $\mathrm{CF}_{s,k,i,j}$ indicates the emission factor of environmental indicator *k* and tableware and packaging type *i* in life-cycle process *j* under scenario *s*; the index *j* shows the life-cycle phase; *k* represents different environmental or resource indicators, including CO_2, SO_2, NO_x, $PM_{2.5}$, dioxin (measured as 2,3,7,8-tetra chlorodibenzo-*p*-dioxin), river water consumption and COD; *s* expresses different tableware management scenarios; *i* represents five types of tableware and cutlery (food container, spoon, wood chopsticks, wooden toothpick and napkin), three types of packaging (packaging bag, cutlery wrapper and toothpick wrapper) and one transport packaging type (corrugated carton).

Takeaway data collection. As there are no publicly available and comprehensive data on the amount of online takeaway orders, street-level takeaway order data were collected from one of the largest Chinese online takeaway platforms, Meituan (http://waimai.meituan.com), making up 59% of China's takeaway market share in 2018 and having more than 250 million users[49]. The platform recorded every takeaway food order for each restaurant in each street within each city over the past 30 days, and we accessed the Meituan website at the beginning of each month (from March to August 2018). The six-month takeaway order information was downloaded and compiled in Microsoft Excel using a web crawler. A total of 2.8 billion street-level takeaway order volumes covered 430,000 restaurants in 353 Chinese cities between February 2018 and July 2018. To better discuss the takeaway environmental impacts at the city level, we aggregated the street takeaway order data to the city level.

The average number of daily online takeaway transactions is 1,534,000, which covers 88% of the actual transaction volume of Meituan in 2018[50]. A total of 82.6% of users choose the takeaway ordering service through the online platform, and 64.1% of consumers order takeaway from Meituan, followed by Ele.me (25%)[41], indicating that the Meituan takeaway order data are representative for exploring the city-level order behaviour differences and the associated environmental impacts of China's online takeaway industry. Assuming that the takeaway order volume follows a uniform distribution over time, the six-month takeaway order volume of Meituan is expanded twofold to represent the annual takeaway order volume, and the takeaway order in the whole industry is determined on the basis of Meituan's market share (Supplementary Table 5).

Scenario design. *Baseline scenario.* The baseline scenario is designed from the current packaging material and waste disposal patterns. Plastic single-use food containers are extensively used in China, representing 90% of the total (polypropylene and polystyrene each making up half)[51,52], while polyethylene-coated paper boxes contribute 10%. The environmental impacts of food containers are calculated by the weighted sum based on their market shares. The spoon is made of polypropylene, and the chopsticks and toothpicks are made of birch wood. The packaging bag is made of low-density polyethylene, the napkin is made of virgin bleached chemical pulp, and the cutlery wrapper and chopstick wrapper are respectively made of biaxially oriented polypropylene and printing paper. A corrugated carton is considered for the primary packaging for tableware transportation and its specification is listed in Supplementary Table 2. A takeaway is delivered by a courier with an electric bike. In China, only Shanghai and Beijing have enforced the waste classified collection policy since July 2019 and May 2020, respectively[20,53]. The post-consumer takeaway packaging waste was mixed with MSW and ended up at an incineration or landfill site, and no waste was recycled.

Paper substitution scenario. To further discuss the environmental mitigation potential of the takeaway industry, we design a paper substitution scenario based on the practical pilot case of Shanghai. Takeaway plastic containers and bags are replaced by paper ones. If food providers fail to implement the new standards, they will face platform-specific punishments, including lower rankings, and cancellation of platform subsidies. Food containers and bags are made of kraft paper, and paper boxes are coated with a polyethylene film. Other tableware and packaging materials and their end-of-life are the same as those used in the baseline scenario.

Tableware sharing scenario. The tableware sharing scenario is designed on the basis of the ideas of a sharing economy. Reusable containers have been successfully adopted in the global takeaway industry. For example, the EcoBox initiative based on deposit-return was developed for transporting meals at restaurants, canteens and takeaway food outlets in Luxembourg. As the largest lunch-box producer in Tokyo, Japan, Tamago-ya delivers 'bento' lunch boxes to local office workers at noon and collects the boxes in the afternoon by courier. The restaurant Yi Kou Liang Shi in Beijing has applied reusable tableware to delivery takeaway food, and 90% of reusable tableware can be collected through a centralized mechanism. Applications in the United States, Europe, Southeast Asia and Austria have demonstrated the feasibility of reusable tableware[54], setting a good example for the implementation of the sharing tableware mechanism in China.

Paper, glass, ceramic, stainless steel and silicone are alternative materials for food containers. Paper containers cannot ensure a tight seal and are not suitable for hot liquid food and soup. Reused glass and ceramic containers are safe for microwave and dishwasher use. For the same volume, glass and ceramic containers are the heaviest, and they are more prone to breakage during delivery than others. Owing to their decreased corrosion and temperature resistance, stainless-steel containers may not be suitable for long-term food storage and delivery. Silicone is considered as an ideal material for food containers, owing to the superiorities of safety, long-term usage (ten-year lifetime for Partita silicone food containers) and easy cleaning. The thermal insulation property can also keep takeaway food warm during delivery. For the above reasons, we selected food-grade silicone as the material for reusable food containers and spoons.

The container is designed with dual compartments, which can be used to store both staple food (that is, rice) and other food types (such as a main dish and side dish), thereby reducing the amount of food packaging consumption by half. A recycled high-density polyethylene nonwoven bag is selected to carry the takeaway as they are tough, durable, cost-effective and reusable (maximum lifespan of 180 uses). The napkin and toothpick wrapper are made from 100% recycled content. A 100% recycled paper napkin is used to wrap the cutlery, and a plastic cutlery wrapper is not required. Chopsticks are made of beech wood with a lifetime of two years and should be replaced every six months from the health perspective. The post-consumer toothpick, napkin, cutlery wrapper, corrugated carton, and broken tableware and cutlery were collected and transported to a recycling facility, and the recycling rate is assumed to be 100%.

Different take-back mechanisms and cleaning methods are considered. The first such scenario is centralized collection with manual washing. Suppliers of snacks and fast food are the biggest players in the Chinese online catering market, making up 44% of the total number of restaurants in 2018[55]. As some snack and fast-food providers do not have space for a dishwasher, sharing tableware is assumed manually washed in the restaurant. The post-consumer tableware is collected at the next delivery and taken back to the restaurant in which the courier picks up a new takeaway order. The other scenario considered is decentralized collection with machine washing. Consumers can return the tableware to collection points from where it is delivered to central cleaning stations by a diesel truck. The cleaning stations equipped with commercial dishwashers are responsible for cleaning and disinfection of tableware and taking it back to the restaurant. Given that shared containers and packaging could all be returned and cleaned on the same day after use, a batch of tableware and packaging with the same amount of average daily takeaway order volume is put on the market and reused for one year. A total of 360 uses for one batch of containers and spoons, and 180 uses for two batches of chopsticks and nonwoven bags, are calculated in this scenario. The tableware sharing scenario is an optimal tableware set and aims to lessen the environmental impact.

LCI. Due to a lack of consistent and systematic LCIs for food packaging products in China, the LCIs for the takeaway industry were compiled from direct measurements (weight), the China Life Cycle Database (CLCD, China-Public 0.8)[56], peer-reviewed literature and manufacturers' data, and data gaps were filled by using the background attributional datasets of Ecoinvent (v3.5)[57,58]. The production of tableware and packaging was considered to be carried out in China (see Extended Data Fig. 4 for manufacturer distributions), and the technology level during the production, transportation and disposal was assumed to be homogeneous within each city.

Production of raw material and tableware. The food containers, spoons, plastic bags, cutlery wrappers and polyethylene films of the paper are made of petroleum-based polymers. Chinese average data for polystyrene and low-density polyethylene granule production from the CLCD have been applied[56]. The data for the production of polypropylene and silicone were taken from the rest of the world (RoW) dataset of Ecoinvent, which contained aggregated data for all processes from raw material extraction until delivery at the plant[57]. The polymers were extruded and thermoformed to the final products of tableware and packaging, while conversion processes, including injection moulding, foaming, blow moulding and stretch blow moulding, were taken from the RoW dataset, Ecoinvent[57], and the losses and auxiliaries in the production process were included. The nonwoven bag is made of nonwoven textiles from polypropylene granules. The data concerning the consumption of nonwoven fabrics, electricity and cotton yarn were collected from the local manufacturer, while the LCI of electricity production was sourced from the Chinese market dataset of electricity, medium voltage (CN) in Ecoinvent[57], and the others came from the RoW dataset.

Paper containers, paper bags, napkins, toothpick wrappers and corrugated board boxes belong to paper products. The CO_2 emission inventories for the production of packaging paper, corrugated board and tissue paper in China were sourced from Chen et al.[59]. The Chinese CO_2, SO_2, NO_x, $PM_{2.5}$ and COD emissions and water inventories for writing paper were collected from Ren[60] to model the production of the toothpick wrapper. The LCIs for kraft paper (bleached and unbleached) were used to model the production of the paper containers and paper bags[57]. The data for the single-walled corrugated board boxes were sourced from the corrugated board box production (RoW) dataset[57]. The data for the production of napkins and 100% recycled printing paper, respectively, were sourced from the tissue paper production (virgin, GLO) and graphic paper production datasets of Ecoinvent[57]. The data for the electricity consumed in cutting the paper and folding it into a small-sized portable napkin was collected from the local manufacturer. The electricity and ethylene-vinyl acetate copolymer consumed in cutting and gluing during toothpick wrapper production were collected from the local manufacturer.

The single-use chopsticks and toothpicks are made from birch with 0.45 $g\,cm^{-3}$ of air-dried density, and the reusable ones are made of beech wood with 0.79 $g\,cm^{-3}$ of air-dried density. The chopstick manufacturing process involves logging, milling, shaping, bleaching, natural drying and polishing, while inputs of electricity, water, SO_2 and paraffin wax were collected from the local manufacturer. The wood effective utilization rate during disposable chopsticks manufacturing was 60%[61]. See Supplementary Table 3 for the unit process and data source of the production of each tableware and packaging type.

Transportation. Transportation includes the transportation of secondary materials for tableware production, tableware production for suppliers and takeaway delivery. The tableware manufacturer distributions at the city level are from Alibaba (https://www.1688.com), one of the largest online wholesale platforms in China. More than 7,000 manufacturers of tableware and packaging are located in the Zhejiang, Guangdong, Jiangsu, Fujian and Shandong provinces of China (Extended Data Fig. 4). The raw materials were assumed to travel 150 km from the raw material production plants to the tableware and packaging manufacturers by a heavy-duty diesel truck[31]. After being packaged in the above provinces, the tableware and packaging were transported to the distribution centres across the country, while the transport route was determined on the basis of the shortest-path principle, and distances are collected from Baidu map (https://map.baidu.com), listed in Supplementary Table 4. Tableware and packaging were then distributed to the retailer, assuming a distance of 150 km (ref. [26]). The LCIs for heavy diesel trucks (18 t) were collected from the CLCD[56]. The transportation of post-consumer tableware from the waste collection plants to the final disposal sites was included in the final disposal phase.

There were 2.7 million Meituan riders in 2018, with 45% of the riders receiving more than 20 orders per day, and 40% of them travelling more than 50 km per day[62]; annual total travel distances and total delivery orders were determined on the basis of these distributions. By dividing the total number of takeaway orders by the annual travel distance, the delivery distance for each order was 2.0 km, identical to the survey results in Wen et al.[28]. The electricity consumption per 100 km of electric bikes is estimated by the voltage, current and endurance mileage[63]. Owing to the large market share, we take a two-wheeled food delivery electric bike produced by Zhuhai Weifan Lithium Battery Technology Co. (48 V, 48 Ah, 155 km) as an example; the charge–discharge efficiency of the lithium battery is 95% and its electricity consumption is 1.56 kWh per 100 km. The electricity consumed per order during takeaway delivery is 0.032 kWh. The life-cycle emission factor for the provincial electricity grid mix in China from Ecoinvent is adopted to reflect the regional environmental differences of electricity production[57].

Utilization. Single-use tableware and packaging produce no additional environmental impact in this process. For the reusable items, impacts of take-back logistics and tableware washing were considered. The energy and water consumed in manual and machine dishwashing were taken from a research report indicating that to clean 74 dishes and achieve the same acceptable level of cleaning performance, manual dishwashing consumed 45.9 l of water and 1.39 kWh of electricity (mainly from hot water), and machine dishwashing consumed only 11.5 l of water and 0.92 kWh of electricity[64]. The authors of that report found that electric dishwashers have a substantial water-saving effect, which is consistent with the finding of a European study[65] and Chinese test reports[66,67]. The amounts of detergent consumed in machine and manual dishwashing were respectively taken from the local manufacturer and Gallego-Schmid et al.[26]. The LCI in the production of water and detergent were taken from the tap water production (RoW) and nonionic surfactant production (RoW) datasets of Ecoinvent[57]. Take-back logistics for centralized collection by courier was included in the tableware delivery phase. The tableware at the collection points is delivered to central cleaning centres and sent back to the restaurants after cleaning and disinfecting (heavy diesel truck, 18 t), assuming a distance of 100 km.

End-of-life. We assumed that the takeaway tableware and packaging in each province were disposed of in the same way. The proportions of incineration and landfill of MSW for each province were collected from the China statistical yearbook[68]. The data for the treatment of waste paper, wood and various waste plastics in municipal incineration and sanitary landfill facilities were sourced from the RoW dataset, Ecoinvent[57]. The dioxin emission factor for Chinese MSW incineration was taken from Ni et al.[69]. The inventories of sorting and recycling of waste plastic, paper and wood were taken from Ecoinvent[57]. Owing to a lack of data on the treatment of waste silicone, treatment of waste polyethylene for recycling was used to estimate the end-of-life impacts of silicone tableware and spoons.

Sensitivity analysis. The LCI datasets from different geographical regions and the weight of tableware and packaging may affect the emission factor and activity data (quantities of raw material and production resources are required). The effects of the LCI datasets from Europe (RER) and RoW, Ecoinvent (v3.5) on environmental impacts were investigated under three scenarios. Since food containers and bags were responsible for more than three-fifths of the entire environmental impacts, a sensitivity analysis of the weights of the containers and bags was then performed. Baseline, paper substitution and tableware sharing scenarios were considered as the benchmarks, and the weights of the containers and bags are designed to be 5% heavier than the benchmarks.

The reuse time is one of the important parameters for evaluating the environmental benefits of shared tableware and packaging[25,54]. Each environmental indicator was calculated to explore how many times reusable packaging should be used to balance out the impacts of one use for single-use alternatives in the baseline and paper substitution scenarios. Since the impact of food delivery is the same, it was excluded from the estimation. The production, transport and end-of-life of corrugated cartons for packaging tableware are excluded. The return rate of the sharing packaging is another parameter with high uncertainty, which mainly relies on the take-back behaviour of the consumer. On the basis of the average return data for the Chinese takeaway restaurant Yi Kou Liang Shi, we assumed that 90% of shared tableware can be collected through a centralized mechanism in a real operation. There is no decentralized collection example in the Chinese takeaway industry, but there is for the express delivery industry. On the basis of the return rate of sharing express packaging in the pilot studies of Zhejiang's universities, 75% of shared tableware is assumed to be collected through a decentralized mechanism in practical applications. This means that the replacement of 1 unit of single-use alternative respectively requires 1.1 and 1.3 units of shared tableware set for centralized and decentralized collection. The effects of the return rate on the environmental differences for each indicator were explored.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The weights of the tableware and packaging and cities' takeaway order data are respectively provided in Supplementary Tables 1 and 5. The LCIs were sourced from manufacturers' data, the CLCD[56], Ecoinvent[57] and literature sources[59,60,69]. All data used in the study are available from the corresponding author upon reasonable request. Source data are provided with this paper.

Code availability

All programming codes are available from the corresponding author upon reasonable request.

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Author contributions

Y.Z. and D.G. designed the study. Y.Z., W.X. and J.L. prepared data. Y.Z. conducted calculations and drafted the manuscript. D.G., Y.Z. and Y.S. led the analysis. Y.Z. and Y.S. drew the figures. All authors participated in discussing the results and contributed to writing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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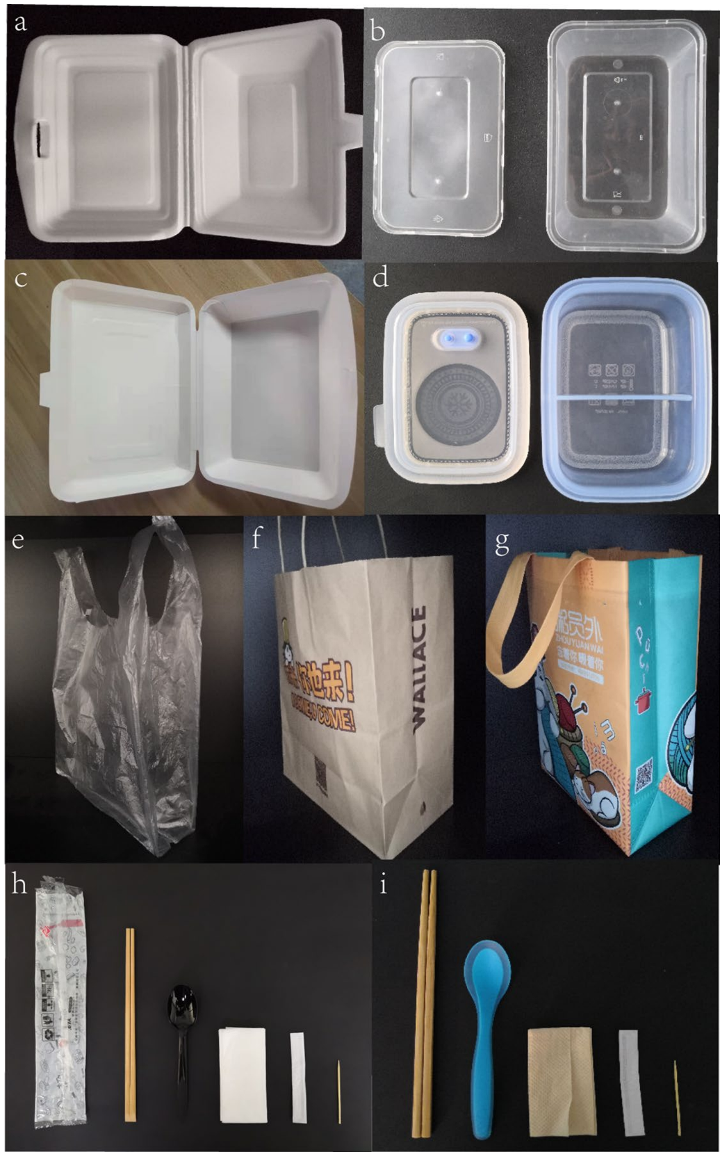
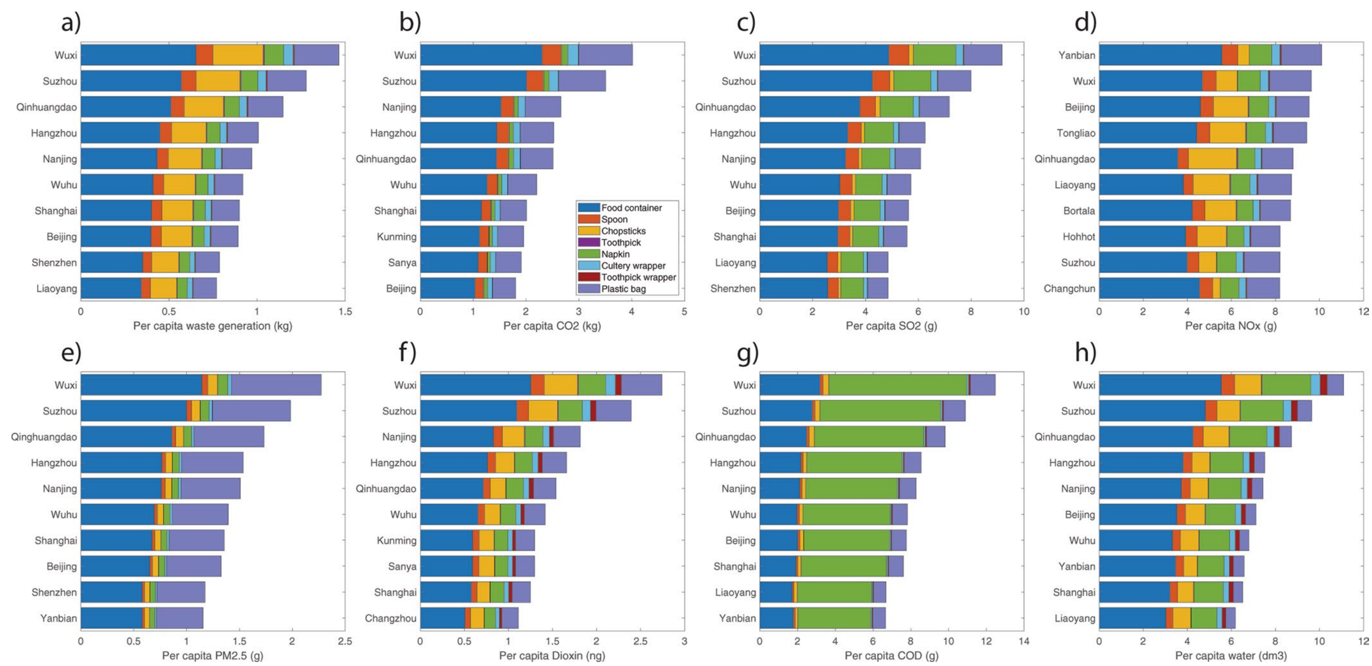
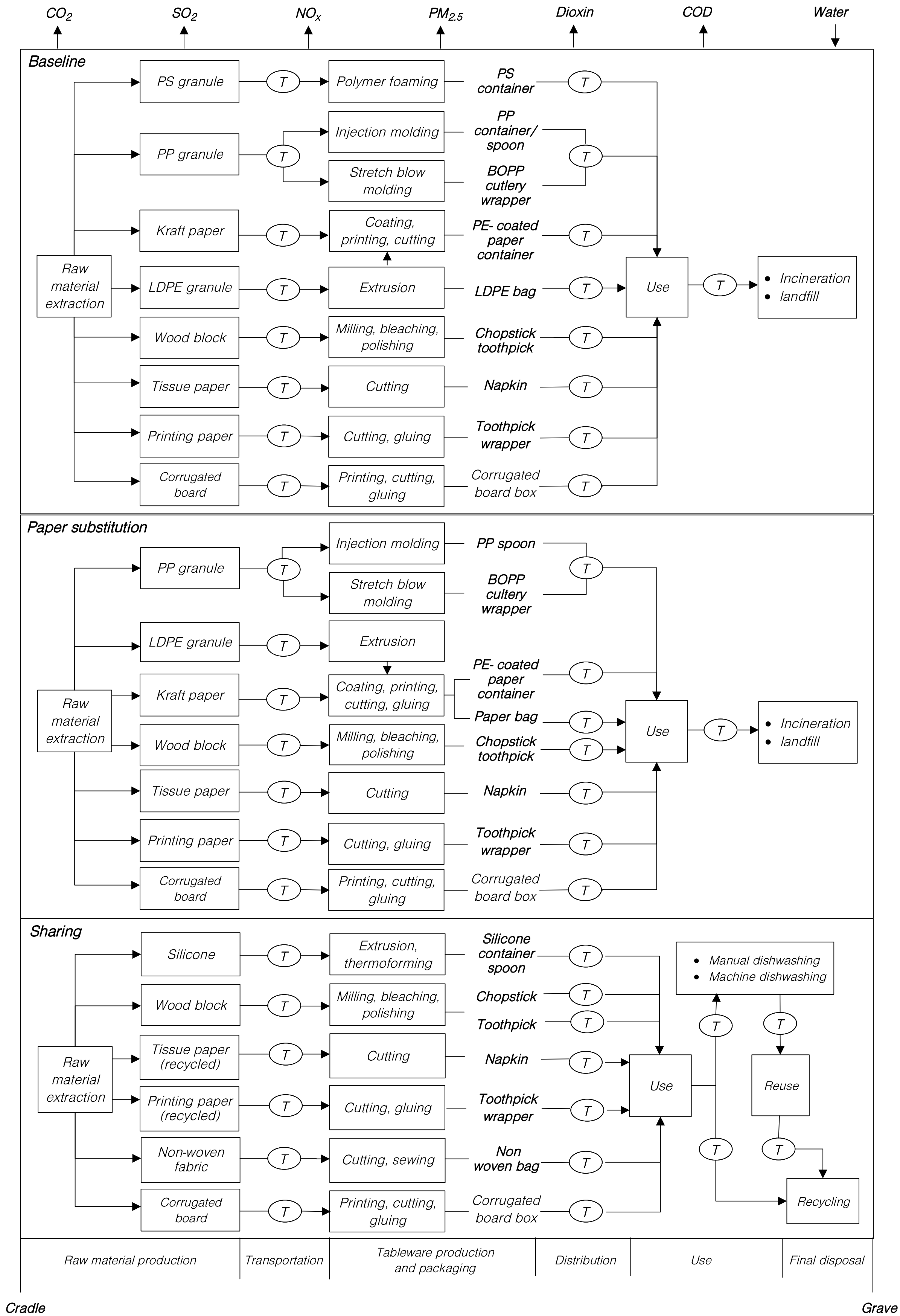


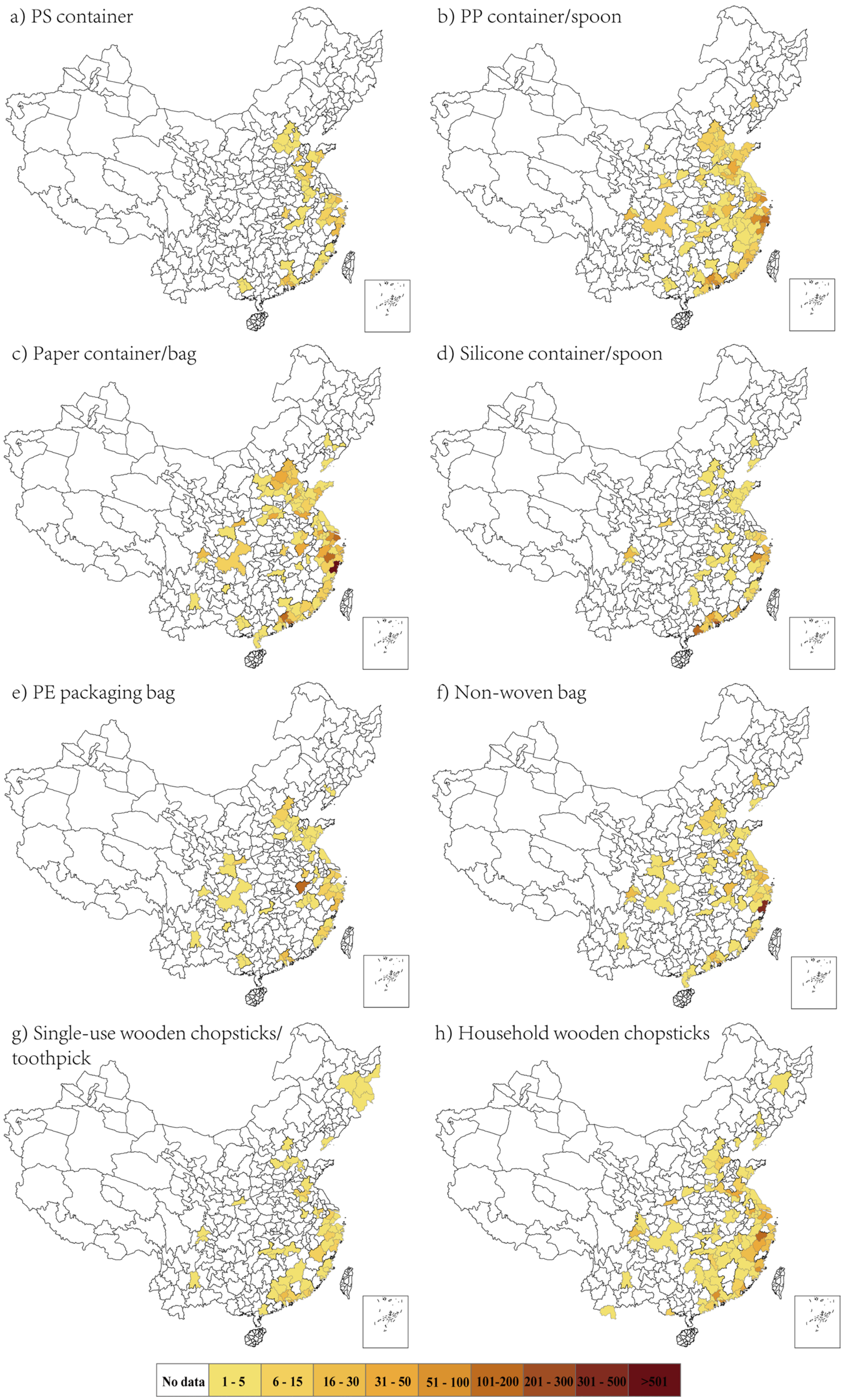
Extended Data Fig. 1 | Types of takeaway tableware and packaging. The tableware sets under baseline (**a**, **b**, **c**, **e** and **h**), paper-substitution (**c**, **f** and **h**), and tableware-sharing (**d**, **g** and **i**) scenarios are shown.



Extended Data Fig. 2 | Top ten cities in per capita takeaway waste generation, emissions and water consumption. The contribution of each tableware and packaging in per capita takeaway waste generation, emissions and water consumption in top ten cities is shown in different colours.



Extended Data Fig. 3 | System boundary for tableware and packaging under scenarios considered in the study. The life cycle phases of tableware and packaging consumed in China's takeaway industry under scenarios are presented. (T—transport).



Extended Data Fig. 4 | Distributions of takeaway tableware and packaging manufacturer in China. The number and location of each type of takeaway tableware and packaging manufacturer are shown.

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Python 3.6.5
Data analysis	Matlab R2014b and Microsoft Excel 2016

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We use a top-down approach with city-level takeaway-order data to explore the packaging waste and life-cycle environmental impacts of takeaway industry in China. We then defined one paper-substitution and two sharing tableware scenarios to simulate the environmental mitigation potentials.
Research sample	As there are no publicly available and comprehensive data on the total number of online takeaway order, we collected the street-level takeaway order data from one of the largest Chinese online takeaway platforms, Meituan (waimai.meituan.com), making up 59% of the country's takeaway market share in 2018. The average daily number of online takeaway transactions come to 1,534,000, which covers 88% of the actual transaction number of Meituan in 2018. 82.6% of users choose online takeaway ordering service by the online platform, and 64.1% consumers would order takeaway by Meituan, followed by Ele.me (25%), indicating Meituan takeaway data is representative for exploring city-level order behavior differences and associated environmental impacts of China's online takeaway industry.
Sampling strategy	The Meituan platform records every takeaway food order for each restaurant in each street within each city over the past 30 days. We accessed Meituan website at the beginning of each month from March to August 2018. Assuming the takeaway order volume follows a uniform distribution over time, six-month takeaway order volume of Meituan is expanded two-fold to represent the annual takeaway order volume, and the takeaway order in the whole industry is determined based on Meituan's market share.
Data collection	The street-level takeaway order was downloaded and compiled in Microsoft Excel using a web crawler. The type, material and specification of the set of tableware and packaging is based on the their market shares from literature and extensive surveys. The life-cycle inventories of the takeaway industry were compiled by direct measurements (weight), manufacturers' data, China life cycle database (CLCD, China-Public 0.8) and literature sources. The background data came from the attributional version of Ecoinvent (version 3.5). The lifespan of sharing tableware and packaging is from manufacturers. The return rates of centralized and decentralized collection is from two practical applications of sharing packaging in China. The manufacturer distributions of tableware and packaging production at city level comes from one of the largest Chinese online wholesale platforms, Alibaba (www.1688.com). The transport route from factory to distribution center is determined based on the shortest path principle, and transport distances are collected from Baidu map (map.baidu.com). The distances from raw material production plants to manufacturers, and from distribution centre to the retailer are from literatures. The takeaway orders received and travel distance of Meituan riders come from Takeaway rider employment report in 2018. The energy and water consumption data of manual and machine washing in China is from a research report, while detergent consumption is from manufacturer of dishwasher and literature. The proportion of incineration and landfill of MSW for each province were collected from the China statistical yearbook. The population, GDP, total retail sales of consumer goods are collected from the China city statistical yearbook.
Timing and spatial scale	The analysis covers 353 Chinese cities, and takeaway waste generation, environmental emissions, and water consumption of China's takeaway industry in 2018 are calculated.
Data exclusions	Packaging with low market share such as aluminum foil container, plastic knives and forks, as well as paper cutlery wrapper, are excluded. We only focus on environmental impacts of takeaway packaging, and the food waste are excluded.
Reproducibility	N/A
Randomization	N/A
Blinding	N/A

Did the study involve field work? ☐ Yes ☒ No

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Materials & experimental systems

n/a	Involved in the study
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☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging