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 kt 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 takeaway industry in China. The ten most wasteful cities, with just 7% of the population, in terms of per capita waste generation produced 30% of the country's takeaway waste, 27%-34% of country's pollutant and 30% of water consumption. We defined one paper-substitution and two sharing tableware scenarios to simulate the environmental mitigation potentials. The results of scenario simulations find that sharing tableware could reduce up to 92% waste generation, more than two-thirds of environmental emissions and water consumption. Such a mechanism provides a potential solution to address the food packaging waste dilemma and a new strategy for promoting sustainable and zero-waste lifestyle.

Introduction

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 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 wastes (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 National Development and Reform Commission (NDRC) and Ministry of Housing and Urban-Rural Development (MHURD) in March 2017 [13], the "zero-waste city" pilot program by General Office of the State Council in January 2019 [14], and a national-wide single-use plastic ban by DNRC and Ministry of Ecological Environment (MEE) in January 2020 [15]. In terms of the priority areas of plastic pollution such as from e-commerce and the takeaway industry, Shanghai Association of Food Contact Materials has, for example, released three non-binding food packaging standards to encourage replacement of plastic food containers and bags with paper bowls and bag, and biodegradable sacks[16-18]. The standards were implemented on a trail basis by three online food delivery platforms in three districts of Shanghai since June 2018 [19]. Shanghai was the first pilot cities to implement the national MSW sorting policy, and the first mandatory regulation on domestic waste management in China has been acted upon in Shanghai on July 1st, 2019, mentioning that restaurant and food delivery business 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 (e.g. container [21-28], cutlery [28-30], and bag [28,31,32]) with different materials (e.g. petroleum-based polymers [21-26,30-33], and bio-based polymers [21,24,27,29,30,32,34,35]) and lifecycle processes. For example, within its lifespan a Tupperware reusable food saver was shown to balance out the life cycle impacts of 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 minimising 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 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 based on 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

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 (visualized in Extended Data Figure 1), which is equal to three-fifths of China's overall MSW generation per day, 13 days of MSW generation in Beijing and one 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 Figure 1~~Figure 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).

***Figure 1 Takeaway packaging waste generated in China, 2018**. The colours show the annual per capita waste generated by cities, and darker regions have higher waste. The takeaway packaging wastes are estimated in a top-down approach that downscales the national packaging consumption into the city-level with takeaway order collected from Meituan online food delivery platform. Takeaway waste generated in Chinese cities vary ~~significantly~~notably, there is no takeaway restaurant information in 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).*

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

***Figure 2 Takeaway packaging waste generated per capital in Chinese cities.** Cities are ranked by per capital takeaway packaging waste after dividing city takeaway packaging wastes by the population.*

The bar charts show the per capita takeaway packaging waste of top and bottom 10 cities, and contribution of each tableware and packaging is shown in different colours.

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 $PM_{2.5}$, 436 mg of dioxin, 2.8kt of COD, and consumed 2.5 million m^3 of water in 2018. Single-use food container, plastic bag, and tissue have higher environmental impacts (85% on average) compared with other tableware. 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 tableware and are responsible for the greatest river water consumption (47%) from tableware. Plastic bag is the second-greatest contributor of emissions of CO_2 (25%), NOx (18%), $PM_{2.5}$ (39%) and dioxin (17%). Napkin makes up the largest share of COD emission (59%) and the second-largest share of SO_2 emission (18%) and water consumption (20%). The results from tableware and life cycle processes are presented in Table 1Table 1. From a lifecycle process perspective, the production of raw material and tableware contributes more than four-fifths of the whole life-cycle environmental impacts (i.e. 96% of SO_2, 92% of $PM_{2.5}$, 89% of COD, and 80% of water). 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 NOx emission, which is 54%).

Table 1 Takeaway environmental impacts by tableware and life cycle processes in China, 2018. *The environmental impacts of the takeaway industry are the sum of life-cycle phases of eight types of tableware and packaging. The environmental impact of each packaging 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 transportation of raw materials for tableware production, tableware production for suppliers and takeaway delivery were aggregated into "Transportation" phase. There is no additional environmental impact in the tableware utilization phase under baseline scenario.*

Indicator	*CO_2*	*SO_2*	*NOx*	*$PM_{2.5}$*	*Dioxin*	*COD*	*Water*
Unit	kt	*t*	*Tt*	*t*	*mg*	*t*	*10^3 m^3*
			By tableware				

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	1412.92	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

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 tableware 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 Jing-Jin-Ji, Yangtze River Delta, and Pearl River Delta owing approximately 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 (see Extended Data Figure 2). See Extended Data Figure 2(b) of top 10 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), Sanya in Hainan province (1.9 kg per capita) have large CO_2 emissions from takeaway.

Figure 3 Life-cycle takeaway CO_2 emission and takeaway Engle's coefficient of China, 2018. *The blue dots represent the takeaway carbon emission per capita of the cities. The larger the dots are, the larger the per capita CO_2 emission estimated by dividing life-cycle CO_2 emissions of eight takeaway packaging by the population. City' colour show their takeaway Engle's coefficient (TEC), defined as the proportion spent on takeaway of the household expenses. Annual takeaway spending of the city is determined by multiplying annual takeaway order volume with 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-value 0.000). There are strong* *correlations between the variables at the 0.01 significance level (2-tailed), indicating that the per capita takeaway CO_2 emission is closely related to the TEC.*

We define takeaway Engle's coefficient (TEC), as shown in Figure 3~~Figure 3~~, to further explore the city-level takeaway spending and lifestyle differences. A higher TEC (darker red in Figure 3~~Figure 3~~) indicates proportionately greater spending on takeout. We find that tourist and rich cities have larger TECs than others, indicating their residents are willing to pay more on takeaway food. Among the top ten cities with high TECs, six are tourist cities, such as 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 (e.g. 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 2640 times higher than that of Loudi, and the takeaway CO_2 emission of Wuxi is 4.01 kg/cap, which is 8 times higher than the national average (0.52 kg/cap) 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 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 two scenarios (see scenario design, Extended Data Figure 1 and Supplementary Table 1 for more details):

(1) Paper-substitution scenario: a set of tableware that includes a polyethylene (PE)-coated kraft paper container; a kraft paper bag; single-use cutlery package, comprising a polypropylene (PP) spoon, a pair of wooden chopsticks, a wooden toothpick and its wrapper, napkin and a biaxially oriented polypropylene (BOPP) chopstick wrapper.

(2) Tableware-sharing scenario: a reusable and returnable tableware set that includes a silicone container (Partita); a reusable high-density polyethylene (HDPE) non-woven bag; a cutlery package (wrapped by 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 takeback mechanisms are considered, including centralized takeback mechanism whereby all tableware will be collected by courier and hand-washed in the restaurant separately, and decentralized takeback mechanism that assumes all the reusable tableware are returned to collection points by consumers and machine-washed in central cleaning stations.

Figure 4 and **Figure 5** show the life-cycle environmental emissions and water consumption by tableware and processes 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% (183kt) 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. Since 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%), COD (66%) emissions, and water consumption (68%). Dioxins are mainly by-products of industrial processes, especially chlorine bleaching of paper pulp, production of raw material (e.g. 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 energy and four times the amount of water, leads to 14 times eutrophication of water bodies, and produces 2.7 times 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 takeaway packaging waste dilemma.

Figure 4 Life-cycle takeaway environmental impacts (air) by tableware and packaging under scenarios. *These bar charts indicate the CO_2 and four air-pollutant emissions by six life-cycle phases and eight tableware and packaging under 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" implies the decentral collection of sharing tableware with machine washing. "Material prod" means production of raw material, and "Tableware prod" denotes 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 process for single-use tableware and packaging, and "recycle" shows the final disposal for reusable items. "Washing" and "Takeback" belong to the utilization of sharing tableware phase, respectively indicating water, electricity, and detergent consumption during the washing process, as well as transport from decentralized tableware collection points to central cleaning centres and send back to restaurants. "Cutl. W." means the cutlery wrapper. "Toot. W." refers to the toothpick wrapper.*

Figure 5 Life-cycle takeaway environmental impacts (water) by tableware and packaging under scenarios*. These bar charts indicate COD emission and water consumption by six life-cycle phases and eight tableware and packaging under baseline (SC-baseline), paper-substitution (SC-paper), and two tableware-sharing scenarios. The abbreviation for scenarios and life-cycle phases are the same as Figure 4.*

Tableware-sharing scenarios have stronger mitigation effects on environmental impacts, reducing takeaway waste by 92% (295 kt including 217 kt plastic waste, 63 kilotons disposable chopsticks, and 13 kt paper waste) and environmental impacts by more than two-third (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 takeback) compared with the baseline scenario. The use of recycled napkins can mitigate more than one-half of environmental impacts (i.e. 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 takeback) 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, COD), followed by transportation (including takeback logistics) and washing phase. For SO_2, NO_x and $PM_{2.5}$ emissions and water consumption, transportation is the main contributor. Life-cycle water consumption of a reusable tableware set is 21 times higher than that of one-way tableware set (see Supplementary Table 9). The water consumption of reusable tableware is only 30% of cumulative one-way tableware in a year period. There are similar tendencies for other indicators, indicating that reusable tableware has resource-saving benefit and environmental mitigation potential.

The decentralized collection scenario has larger SO_2, NO_X, COD emissions than centralized takeback due to the extra impacts of takeback logistics. Takeback transportation contributes 4% of CO_2 emissions, less than 16% of air pollutant emissions (SO_2, $PM_{2.5}$, dioxin) and water consumption, and 21% of COD emissions, but contribute 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, 2000 m^3 water, and 1.4 kt detergent, corresponding to reducing more than one third of environmental impact of washing process (i.e. 34% of CO_2, SO_2, NO_x, $PM_{2.5}$, and 35% dioxin, COD and water).

Discussions and policy implications

To deal with the problem of takeaway packaging waste in China, policy-makers need specific information on the environmental impacts of the takeaway industry. We develop 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 potential environmental impacts of different management strategies are indicated that tableware sharing is an effective and sustainable way to lessen the environmental impact of the takeaway industry.

Results of the sensitivity analysis demonstrated that life-cycle inventory datasets from different geographic regions have ~~significant~~ notable impacts on the results (see Supplementary Table 7). The baseline scenario is less sensitive than the paper-substitution scenario. The effects of life cycle inventory (LCI) datasets on 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, NOx, COD, and dioxin emissions is more sensitive than other lifecycle phases. If the weights of food container and bag were increased by 5%, their environmental impacts would increase by 1% to 4% (see Supplementary Table 8). Paper containers and bags are more sensitive to 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 under 90% and 75% of return rate, shared tableware requires 20 reuses to offset the impact of the disposable item in 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 amongst government, restaurants, food delivery platforms, and consumers. Measures for the supervision and administration of takeaway food safety [45] and food safety operation specifications [46] have been acted upon in the online takeaway services of China since 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 ~~inspect~~ 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 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 industry of retail, catering, and logistics to create a zero-waste society. By comparing life-cycle environmental impacts of sharing takeaway packaging with single-use items, we hope that tableware-sharing can serve as a feasible solution for reducing food delivery packaging waste that many cities around the globe struggle with, help integrated policy-making 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 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 calculate them as a tableware set due to the data limitation. Life-cycle inventories for seven environmental indicators were compiled, impact category indicators are quantified to assess the effects of takeaway industry on the environment and human health. We only focus on environmental impacts of takeaway packaging, and the food waste are excluded. A population's acceptance and human behavioral change under the sharing mechanism is a good point to explore the environmental impacts of food waste.

Methods

Life-cycle environmental impacts of China's takeaway industry were estimated under three scenarios (see scenario design), while potential environmental mitigation strategies with different packaging materials and management mechanisms were explored. System boundary and function unit was production, packaging, transportation, utilization, and disposal of annual tableware and packaging consumed in China's takeaway industry (see Extended Data Figure 3), and the production of machinery and infrastructure was excluded. Since cutlery, napkins, and chopsticks are habitually bundled with takeaway orders, and each takeaway is assumed to be equipped with a set of tableware and packaging (see Extended Data Figure 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 impacts was calculated by multiplying the consumption of tableware and packaging by the corresponding emission factor (see Equation 1).

$$EF_{s,k} = \sum_{i=1}^{I}\sum_{j=1}^{J} AD_{s,i} \cdot CF_{s,k,i,j} \qquad \textit{Equation 1}$$

where $EF_{k,s}$ represents the environmental emission and water resource consumption of environmental indicator *k* under scenario *s*; $AD_{s,i}$ denotes the annual takeaway or packaging i consumption related to takeaway order amount under scenario *s* ; $CF_{s,k,i,j}$ indicates the emission factor of environmental indicator *k* and tableware and packaging type i in life cycle process j under scenario *s*; Index j shows the life cycle phase; *k* represents different environmental or resource indicators, including carbon dioxide, sulfur dioxide, nitrogen oxides, particulates less than 2.5 µm, dioxin (measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin), river water consumption, and chemical oxygen demand; *s* expresses different tableware management scenarios; i represents five types of tableware and cutlery (food container, spoon, wood chopsticks, wooden toothpick, napkin), three types of packaging (packaging bag, cutlery wrapper, toothpick wrapper) and one transport packaging (corrugated carton).

Takeaway data collection

As there are no publicly available and comprehensive data on the amount of online takeaway order, the street-level takeaway order data was collected from one of the largest Chinese online takeaway platforms, Meituan (waimai.meituan.com), making up 59% of the 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 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. 2.8 billion street-level takeaway order volumes covered 430,000 restaurants in 353 Chinese cities between February 2018 to July 2018. To better discuss the takeaway environmental impacts in the city level, we aggregated the street takeaway order data to the city-level.

The average daily online takeaway transactions come to 1,534,000, which covers 88% of the actual transaction volume of Meituan in 2018 [50]. 82.6% of users choose takeaway ordering service through the online platform, and 64.1% consumers order takeaway from Meituan, followed by Ele.me (25%) [41], indicating Meituan takeaway order data is representative for exploring city-level order behavior difference and associated environmental impacts of China's online takeaway industry. 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 (see 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, occupying 90% of total (polypropylene (PP) and polystyrene (PS) each half) [51,52], while the polyethylene (PE)-coated paper box contributes 10%. The environmental impacts of food container are calculated by the weighted sum based on their market shares. The spoon is made of PP, and chopsticks and toothpicks are made of birch wood. The packaging bag is made of low-density polyethylene (LDPE), the napkin is made of virgin bleached chemical pulp, and the cutlery wrapper and chopstick wrapper are respectively made of biaxially oriented polypropylene (BOPP) 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 the electric bike. In China, only Shanghai and Beijing have enforced the waste classified collection policy since July 2019 and May 2020[20,53]. The post-consumer takeaway packaging waste was mixed with municipal solid waste 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 substituted by paper ones. If food providers fail to implement the new standards, they will face platform-specific punishments, including lower rankings, and canceling platform subsidies. Food containers and bags are made of kraft paper, and paper box is coated by PE 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 based on ideas of sharing economy. Reusable containers have been successfully adopted in global takeaway industry. For example, the EcoBox initiative based on deposit-return is developed for transporting meals at the restaurant, canteen, and takeaway food outlet in Luxembourg. As the largest lunch box producer in Tokyo, Japan, Tamago-ya company delivers "bento" lunch boxes to local office workers at noon and collects the box in the afternoon by the courier. A restaurant named Yi Kou Liang Shi in Beijing has applied reusable tableware to delivery takeaway food, 90% of reusable tableware can be centralizedly collected. The applications in the United States, Europe, Southeast Asia, and Austria have demonstrated the feasibility of the reusable tableware [54], which set a good example for the sharing tableware mechanism implementation of China.

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

The container is designed with dual compartments, which can be used to store both staple food (i.e. rice) and dishes, thereby reducing the numbers of food packaging consumption by one-half. A recycled HDPE non-woven 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. 100% recycled napkin paper is used to wrap the cutlery, and 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%.

Differentiated takeback mechanisms and cleaning ways are considered: (1) Centralized collection with manual washing. Snacks and fast food are the biggest players in Chinese online catering market, contributing 44% of the total number of restaurants in 2018 [55]. As some snack and fast food providers do not have space for 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. (2) Decentralized collection with machine washing. Consumers can return the tableware to collection points from where it is delivered to central cleaning stations by diesel truck. The cleaning stations equipped with commercial dishwashers are responsible for cleaning and disinfection of tableware and taking back to the restaurant. Given that shared containers and packaging could be all 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. 360 uses for one batch of containers and spoons, and 180 uses for two batches of chopsticks and non-woven bags, are calculated in this scenario. The tableware-sharing scenario is an optimal tableware set and aims to lessen environmental impact.

Life-cycle inventory

Due to a lack of consistent and systematic life cycle inventory of food packaging products in China, the life-cycle inventories of the takeaway industry were compiled by direct measurements (weight), China life cycle database (CLCD, China-Public 0.8) [56], peer-reviewed literature and manufacturers' data, and data gaps were filled by the background attributional datasets of Ecoinvent (v3.5) [57,58]. The production of tableware and packaging was considered to be in China (see Extended Data Figure 4 for manufacturer distributions), and the technology level during the production, transportation, and disposal was assumed to be homogenous within each city.

Production of raw material and tableware

The food container, spoon, plastic bag, cutlery wrapper, and PE film of the paper are made of petroleum-based polymers. Chinese average data of PS and LDPE granule production from CLCD have been applied [56]. The production of PP and silicone came from the rest of the world (RoW) of Ecoinvent, which was aggregated data for all processes from raw material extraction until delivery at plant [57]. The polymers were extruded and thermoformed to final products of tableware and packaging, while conversion processes, including injection moulding, foaming, blow moulding and stretch blow moulding came 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 PP granules. The consumptions of nonwoven fabrics, electricity, and cotton yarn were from the local manufacturer, while LCI of electricity production was sourced from market for electricity, medium voltage (CN) dataset in Ecoinvent[57], and others came from RoW dataset.

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

Single-use chopstick and toothpick are made from birch with 0.45 g/cm^3 of air-dried density, and 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, sulfur dioxide and paraffin wax came from local manufacturer. The wood effective utilization rate during disposable chopsticks manufacturing was 60% [61]. See Supplementary Table 3 for unit process and data source of production of each tableware and packaging.

Transportation

Transportation includes the transportation of secondary materials for tableware production, tableware production for suppliers and takeaway delivery. The tableware manufacturer distributions at city level came from Alibaba (www.1688.com), one of the largest online wholesale platforms in China. More than 7,000 manufacturers of tableware and packaging are located in Zhejiang, Guangdong, Jiangsu, Fujian and Shandong Provinces of China (see Extended Data Figure 4). The raw materials were assumed to travel 150 km from 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 was transported to the distribution centre across the country, while the transport route was determined based on the shortest path principle, and distances are collected from Baidu map (map.baidu.com) listed in Supplementary Table 4. Tableware and packaging were then distributed to the retailer, assuming a distance of 150 km [26]. Life-cycle inventories for heavy diesel truck (18 tonnes) were collected from CLCD [56]. The transportation of post-consumer tableware from waste collection plants to the final disposal sites was included in the final disposal phase.

There are 2.7 million Meituan riders in 2018, 45% of the riders receiving more than 20 orders per day, and 40% of the riders travel more than 50 kilometres per day[62], and annual total travel distances and total delivery orders were determined based on these distributions. By dividing the total number of takeaway orders by annual travel distance, the delivery distance of each order was 2.0 km, identical with survey results in Wen, et al. [28] . Electricity consumption per 100 km of electric bikes is estimated by the voltage, current and endurance mileage [63]. Due to the large market share, we take two-wheeled food delivery electric bike produced in Zhuhai Weifan Lithium battery technology co. LTD (48V, 48AH, 155km) for example, the charge-discharge efficiency of lithium battery is 95% and its electricity consumption is 1.56 kWh per 100 km. Electricity consumed per order during takeaway delivery is 0.032 kWh. The life cycle emission factor of 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 takeback logistics and tableware washing were considered. The energy and water consumed in manual and machine dishwashing were from a research report, indicating to clean 74 dishes and achieve the same acceptable level of cleaning performance, manual dishwashing consumed 45.9 litres of water and 1.39 kWh of electricity (mainly from hot water), and machine dishwashing only consumed 11.5 litres of water and 0.92 kWh of electricity[64]. They found that electric dishwashers have a substantial~~significant~~ water-saving effect, which is consistent with the finding of Europe study [65] and Chinese test reports [66,67]. The detergent consumed in machine and manual dishwashing was respectively from the local manufacturer and Gallego-Schmid, et al. [26]. The life cycle inventory in production of water and detergent come from tap water production (RoW) and non-ionic surfactant production (RoW) of Ecoinvent [57]. Takeback logistics for centralized collection by courier was included in the tableware delivery phase. The tableware in collection points is delivered to central cleaning centre and sent back to restaurants after cleaning and disinfecting (heavy diesel truck, 18 tonnes), assuming a distance of 100 km.

End-of-life

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

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 required). The effects of LCI datasets from Europe (RER) and RoW, Ecoinvent (V3.5) on environmental impacts were investigated under three scenarios. Since food container and bag was responsible for more than three-fifth of entire environmental impacts, the sensitivity analysis of weights of container and bag was then performed. Baseline, paper substitution and tableware sharing scenarios were considered as the benchmarks and the weights of container and bag are designed 5% heavier than the benchmark.

The reuse time is one of the ~~significant~~ 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 carton for packaging tableware is excluded. The return rate of sharing packaging is another parameter with high uncertainty, which mainly relies on the takeback behaviour of consumer. Based on the average return data of a Chinese takeaway restaurant named Yi Kou Liang Shi, we assumed 90% of shared-tableware can be centralizedly collected in real operation. There is no decentralized collection example in the Chinese takeaway industry but the express delivery industry. Based on the return rate of sharing express packaging in pilots of Zhejiang's universities, 75% of shared tableware is assumed to be decentralized collected in practical application. It means that to replace one unit of single-use alternative, it is respectively required 1.1 unit and 1.3 unit of shared tableware set for centralized and decentralized collection. The effects of return rate on the environmental differences ~~in~~ for each indicator were explored.

Data availability

The weight of tableware and packaging and cities' takeaway order data are respectively provided in Supplementary Table 1 and Supplementary Table 5. The life-cycle inventories are sourced from manufacturers’ data, China life cycle database [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.

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 (Y.Z, Y.S., D.G, X.L., Y.C., J.L., W.X., J.X., Z.M. and Z.Y.) participated in discussing the results and contributed to writing the manuscript.

Competing interests

The authors declare no competing interest.

Additional information

Extended data is available for this paper.

Supplementary information is available for this paper.

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