frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 28 February 2025
DOI 10.3389/fsufs.2025.1502264

OPEN ACCESS

EDITED BY
Wenbo Li,
Jiangsu Normal University, China

REVIEWED BY
Isaac Odun-Ayo,
Chrisland University, Nigeria
Xin Xiong,
Southwest Jiaotong University, China

*CORRESPONDENCE
Li Zhang
✉ zhangli2106@163.com

RECEIVED 26 September 2024
ACCEPTED 11 February 2025
PUBLISHED 28 February 2025

CITATION
Zhang L, Ye L, Qian L, Han J, Zuo X and Li Y (2025) The association between refrigerator use and carbon footprint of household food waste: empirical evidence from China. *Front. Sustain. Food Syst.* 9:1502264. doi: 10.3389/fsufs.2025.1502264

The association between refrigerator use and carbon footprint of household food waste: empirical evidence from China

Li Zhang[1]*, Linxiang Ye[1], Long Qian[1], Jingwei Han[1], Xiuping Zuo[2] and Yuting Li[1]

[1]Nanjing University of Finance and Economics, Nanjing, China, [2]Jiangsu Open University, Nanjing, China

Food waste in household settings contributes 66% of the global carbon footprint of food waste. Reducing food waste at the household level is essential for global environmental sustainability. Based on the China Health and Nutrition Survey (CHNS) and the China Food Life Cycle Assessment Database (CFLCAD), this paper explores the resource and environmental impacts of food waste from the perspective of the use of refrigeration equipment as a refrigerator in Chinese households, and based on life cycle theory. The primary findings are that (1) Refrigerator use significantly reduces the carbon footprint of household food waste. (2) Dietary knowledge plays a moderating role in the food waste carbon footprint effect of refrigerator use. (3) Heterogeneity analyses show that the effect of refrigerator use on household food waste carbon footprint varies according to the gender and education level of the household head, household per capita income level and urban-rural type. This paper provides evidence that the popularization of refrigerators reduces the carbon footprint of household food waste in China, which may have implications for other countries.

KEYWORDS

food waste, refrigerator use, carbon footprint, China, household

1 Introduction

Global greenhouse gas (GHG) emissions have been on the rise for the past few decades. According to the International Energy Agency report, the total global energy-related carbon dioxide emissions in 2022 amounted to 36.8 Gt, a record high (Adelodun et al., 2021). Among the numerous sources of carbon emissions, the problem of food waste-related carbon emissions has been neglected (Ananda et al., 2022). In fact, food waste not only threatens food security, but also leads to significant resource wastage and brings a series of adverse environmental effects that cannot be ignored (Aschemann-Witzel, 2016; Berjan et al., 2022). These negative effects include a variety of environmentally harmful manifestations arising from agricultural production, processing and manufacturing, as well as food transportation and storage, of which greenhouse gas emissions (GHGEs) are one of the most representative one (Boehm et al., 2018). It has been shown that the global food system emits the equivalent of 18 Gt CO_2eq per year, accounting for 34% of total GHGEs (Bolwig et al., 2021), with the carbon footprint of food waste alone amounting to 4.4 Gt CO_2eq (Brancoli et al., 2017). A study by the EAT-Lancet Commission suggested that if global food loss and waste were halved, then at least 5% of agricultural GHG emissions could be reduced (Brown et al., 2014). It is evident that effective reduction of food waste and its carbon footprint is imperative for environmental sustainability (Cai et al., 2022).

Since the 21st century, the "contribution" of waste in the agricultural food system to global greenhouse gas emissions has been increasing, of which 66% comes from household-level waste (Cheng et al., 2022). As a result, more and more scholars have begun to pay attention to the study of the carbon footprint of household food waste. Through literature review, it is found that research focuses on the following two aspects. One is to measure the national or regional carbon footprint of food waste. Aschemann-Witzel (2016), in quantifying the GHG emissions of various links in the food supply chain in the UK, found that the carbon emissions from food waste in the household sector were 2,500 kg CO_2eq/t. Conrad et al. (2018), based on 65 households in Oakville, Ontario, Canada, with seven consecutive days of tracking survey data, found that their food waste carbon footprint was 742.47 kg CO_2eq/week. Crippa et al. (2021) used the Environmental-Economic Footprint Index to measure the carbon footprint of food waste in Daegu, South Korea, and finding that their food waste carbon footprint per household per day was about 0.71 kg CO_2eq. In a study in Germany, Cuček et al. (2012) found that food waste carbon emissions accounted for 1/4 of the total national carbon emissions. Cheng et al. (2022) derived a per capita food waste carbon footprint of 30 kg CO_2eq in China in 2019 by matching between food consumption and waste data. Among them, 30.84 kg CO_2eq was found in urban areas and 28.58 kg CO_2eq in rural areas. Considering food categories, Davenport et al. (2019) showed that beef and bread waste have the highest carbon footprint. Crippa et al. (2021) revealed that food waste of animal origin has higher environmental and economic losses compared to cereals, fruits and vegetables. However, Ding et al. (2022), based on the fact that the total amount of fruit and vegetable wastage is high, concluded that the environmental impact of fruit and vegetable wastage is equally not negligible.

Secondly, it focuses on how to reduce the carbon footprint of food waste. On the one hand, some scholars have taken the perspective of food conservation and recycling to reduce the amount of food waste and its carbon footprint (Ananda et al., 2022). The UK government has launched a waste and resource action program called "Love Food, Hate Waste" to encourage people to save food (Eberle and Fels, 2016). Some European countries, such as Spain, Italy, and Germany, have implemented waste segregation and paid recycling policies regarding household food waste (Ellison and Lusk, 2018). In addition, Optimizing food waste disposal options is also a good way to reduce the carbon footprint of food waste. A study based on Canadian composting data found that food waste composting would reduce the carbon footprint by 138 million tons (Eriksson et al., 2015). Meanwhile, the carbon footprint of food waste can be reduced through food recycling and moderate composting (European Commission, 2018), food donation, anaerobic digestion, and energy recovery (Fami et al., 2019), and support for the diversion of discarded food to animal feed or for anaerobic digestion (FAO, 2019). On the other hand, scholars are restructuring food consumption from a sustainable dietary perspective. Finkbeiner (2009) proposed that technological approaches have not reduced the demand for carbon footprint-intensive foods, and therefore, greater choices of food consumption with lower carbon footprints might be an effective means of reducing global food-related carbon emissions. Giordano and Franco (2021), based on a study for Vienna, concluded that changes in urban food preferences would significantly reduce GHG emissions. Gooch et al. (2022) mentioned that the Mediterranean diet, which is mainly based on plant-based foods and minimizes red meat intake, etc., is a more desirable dietary pattern for reducing carbon emissions from food waste, as it maintains human health while also promoting environmental sustainability.

Food waste is mostly related to race, age, education, family size, shared meal preparation, cost, geography, preferences, perceptions, and attitudes (Grant and Rossi, 2022; Gustavsson et al., 2013; Hamilton and Richards, 2019; Holsteijn and Kemna, 2018; IEA, 2022; Lauk et al., 2022). However, an evolving awareness has emerged in recent years, with some scholars beginning to focus on the impact of household food storage conditions on food waste and its carbon footprint (Lee et al., 2021). It is estimated that about two-thirds of food and beverages are stored in household refrigeration equipment, such as refrigerators or freezers, prior to consumption or disposal (Li et al., 2021). Relative to ambient conditions, the application of refrigeration equipment such as refrigerators helps to delay food spoilage, allowing ingredients to have a longer shelf-life (Liu et al., 2023). Liu et al. (2024) argued that lowering the temperature of the refrigerator to 4°C significantly extends the storage life and provides more opportunities to use the product. Rasines et al. (Min et al., 2021) argued that for long-term storage, using bags and storing food at 5°C help to reduce food waste with the lowest environmental footprint. When the price elasticity of household food demand was taken into account, Hamilton and Richards (Moult et al., 2018) gave a different conclusion, suggesting that households with refrigerators hoarded more perishable food, thus increasing food waste. This implies that the impact of improved household storage conditions, such as the use of refrigerators, on the carbon footprint of food waste has not yet been agreed upon in the theoretical community. Moreover, existing studies on the impact of refrigerator use on the carbon footprint of food waste are few and mostly qualitative.

Through literature review, it is found that the existing studies are mainly from western developed countries, such as the United Kingdom, the Netherlands, the United States, Portugal, Germany, Canada and so on. There are not many studies on emerging developing countries such as China (Ponis et al., 2017; Qi and Roe, 2016). However, with the rapid development of the economy and society and the steady improvement of people's living standards, the contribution of developing countries to the total global food waste and GHG emissions is increasing (Qi et al., 2020; Qian et al., 2022a). China in the process of development has a population of more than 1.4 billion people, which is one of the most populous countries in the world. Having a large population means that the total amount of food consumed and wasted will be relatively high as well. Qian et al. (2022b), through a survey of 17,110 household members in China, found that an average of 16 kg of food is wasted per person per year at home, equivalent to a carbon footprint of 40 kg of carbon dioxide. If the population base is taken into account, Chinese household food waste and its carbon footprint should not be underestimated. In addition, China is the second largest economy in the world. As the standard of living continues to improve with economic development and urbanization, food consumption habits are changing, and slight changes in the consumption structure will have a significant impact on food waste and its carbon footprint, which in turn will affect the total amount of carbon dioxide emissions. It is reported that in 2019, China's CO_2 emissions reached 14.09 billion tons, accounting for about 27% of the total global GHG emissions (Quested and Parry, 2017). As one of the major GHG emitters, it is of great significance for China to identify the sources of emissions and promote energy conservation and emission reduction. Reducing the carbon footprint of food waste in developing countries, such as China, will contribute to the realization of global carbon reduction targets. Unfortunately, research on food waste and carbon emissions in Chinese households is rare. Therefore, this paper aims to quantitatively analyze the impact of household refrigerator use on the carbon footprint of food waste, and to propose a specific path to reduce the carbon footprint of food waste by focusing on the carbon footprint of household food waste in the context of the rapid increase in refrigerator use in China.

The potential contribution of this paper is to investigate the carbon footprint of household food waste from the life cycle theory, based on the China Health and Nutrition Survey (CHNS) and the China Food Life Cycle Assessment Database (CFLCAD) through the innovative perspective of household refrigerator use. It aims to explore the carbon footprint effect of food waste from household refrigerator use. As household refrigerators are becoming more and more popular in developing countries, this finding may provide valuable insights for other developing countries, as well as a reference for the path to achieve the global goal of "energy saving and emission reduction."

The subsequent arrangement of this paper is as follows: the second part is the research design, including data sources, carbon footprint measurement, variable and model settings; the third part is the empirical results and analysis; the fourth part is the discussion; and the last part is the conclusions and implications.

2 Methods

2.1 Data sources

The data used in this paper come from the China Health and Nutrition Survey (CHNS), a collaboration between the University of North Carolina Population Center and the National Institute of Nutrition and Food Safety of the Chinese Center for Disease Control and Prevention, and the China Food Life Cycle Assessment Database (CFLCAD). The CHNS survey includes 10 waves from 1989, 1991, 1993, 1997, 2000, 2004, 2006, 2009, 2011, and 2015, covering Beijing, Liaoning, Heilongjiang, Shanghai, Yunnan, Jiangsu, Shandong, Henan, Hubei, Zhejiang, Hunan, Guangxi, Guizhou, Chongqing, and Shaanxi provinces. The latest survey data published in the CHNS database are for 2015, but no dietary data for 1989 and 2015. The dietary data for 2011 only include consumption on cooking oil and condiments. Data from surveys prior to 2004 are not taken into account because the Food Composition Tables (FCT) are used with missing data, duplicates and wrong rows, which makes it difficult to calculate the carbon footprint of household food waste.[1] Given the long life cycle of refrigerator use and the small yearly differences in household refrigerator ownership during the survey period, e.g., for households owning a refrigerator in 2004, the ownership of refrigerators remains more or less the same in 2006 and 2009, the trend of changes in the carbon footprint of food waste and refrigerator use is not consistent. In this paper, only the 2009 data are used for the study. The China Food Life Cycle Assessment Database (CFLCAD) is a database covering 17 food groups organized by Rasines et al. (2023) through a literature review based on the collection of GHG emissions from 80 food items. Its food categories correspond to the Chinese Food Composition Table (CFCT) and have unique food codes, which can accurately estimate the environmental footprint of Chinese people's food consumption.

In this paper, the data were cleaned as follows: first, samples of households with serious missing data information were excluded based on the completeness of information on key variables such as refrigerator use. To minimize the interference of abnormal data with the results, samples of households with total food preparation for 3 days less than 0 were excluded, and households' food preparation and food waste for 3 days were reduced-tailed at 1% and 99%. Finally, 4,515 sample observations were obtained.

2.2 Carbon footprint measurement

The concept of "carbon footprint" originates from "ecological footprint" and being often used to characterize greenhouse gas (GHG) emissions and global warming potential (GWP) (Scholz et al., 2015). Currently, the theory of carbon footprint is still in the developmental stage and no consensus has been reached. In this paper, a carbon footprint is the amount of greenhouse gas emissions, expressed in carbon dioxide equivalents (CO_2eq), that are directly or indirectly generated by an activity or product as a result of economic activity over its entire life cycle (Scialabba, 2015).

Based on the China Food Life Cycle Assessment Database (CFLCAD), this paper categorizes the food life cycle into six stages: farm, processing, transportation, storage, packaging, and home meal preparation, as shown in Figure 1.

The carbon footprint of food is equal to the greenhouse gas (GHG) emissions directly or indirectly generated during the food life cycle. The specific formula for calculating carbon footprint is as follows:

$$CF = \sum_{i=0}^{13} (FW_i \times \xi_i) \tag{1}$$

Where CF is the carbon footprint of food waste (g CO_2eq) of a typical household. FW_i is the amount of food waste (g) of the ith food type. ξ_i is the carbon footprint coefficient of the ith food type. Drawing on the viewpoint of Rasines et al. (2023), the food consumed by households on a daily basis is classified into 13

1 The 1991 and 1993 surveys used the Food Composition Table published by China in 1980; the 1997 and 2000 surveys used the Food Composition Table published by China in 1991; The Food Composition Tables published by China in 2002 and 2004 were used in 2004, 2006 and 2009 at the same time.

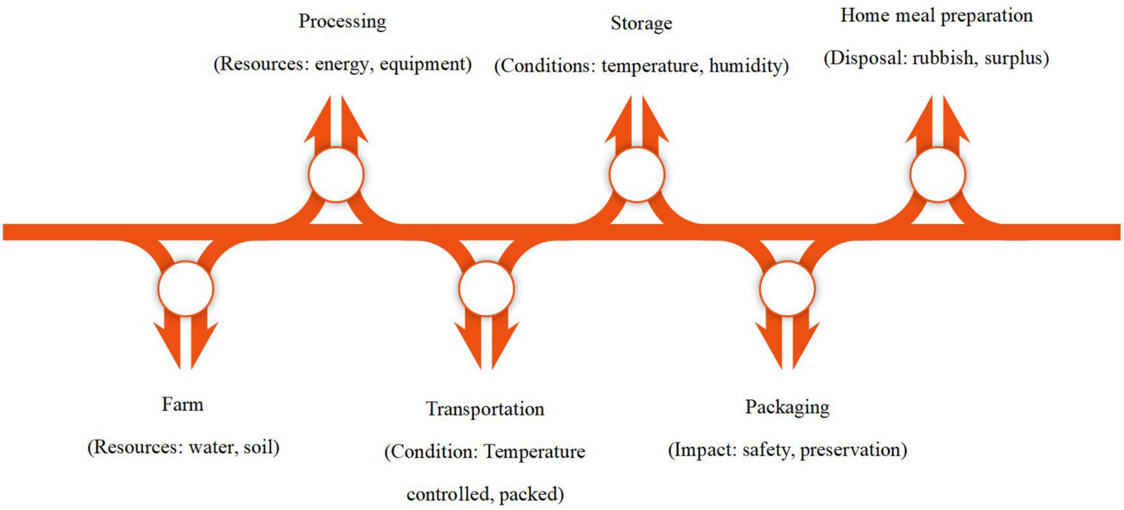

FIGURE 1
System boundaries for food life cycle.

TABLE 1 Carbon footprint coefficients of food categories.

Food group	Carbon footprint coefficient	Food group	Carbon footprint coefficient
Cereals	1.016	Meat	5.134
Starches	0.291	Poultry	3.784
Legumes	0.832	Dairy	1.297
Vegetables	0.266	Eggs	2.890
Fungi and algae	0.930	Aquatic products	7.029
Fruits	0.353	Fats and oils	1.822
Seeds	0.695		

The carbon footprint coefficients were taken from the literature published by Cai et al. (2022).

categories. The carbon footprint coefficients of the food in each category concerned are organized in Table 1.

2.3 Variable settings

2.3.1 Food waste

Food waste refers to the loss of food that can be avoided in the consumption process under the existing conditions, excluding inedible parts such as vegetable peels, bean dregs, and bones (Secondi et al., 2015). Regarding the measurement of food waste in residential households, based on data availability, scholars mostly regard the amount of food discarded on three consecutive days as the amount of food waste directly (Smith and Landry, 2021). This paper also adopts such methods to obtain food waste data, and characterizes the level of food waste by the amount of food waste from the correlation between the amount of food wasted and the amount of food prepared. Accordingly, Equation 1 is calculated to obtain the food waste carbon footprint.

2.3.2 Household refrigerator use

Based on data availability, a binary dummy variable of whether a household owns a refrigerator is often used to measure refrigerator usage.

2.3.3 Control variables

Referring to the existing literature (Smith and Landry, 2021; Song et al., 2015) and based on data availability, this paper introduces multiple variables in the dimensions of household head characteristics, family characteristics, etc., to mitigate the omitted variables problem as much as possible.

Specifically, because the head of household has a decision-making role in household purchases and consumption, the sex, age, education, ethnicity, dietary knowledge, dietary preferences and employment status of the head of household are controlled. Household level variables include the proportion of meals eaten away from home, log household per capita income, household size, proportion of household members under 14 years old, proportion over 60 years old, and average BMI of household members. In addition, the level of community development, north-south region, and urban-rural type are also introduced to control for the possible effects of community and geographic level factors. Definitions and descriptive statistics for each variable are shown in Table 2.

2.4 Model setting

Referring to Lee et al. (2021) and Thapa et al. (2022), the following model is developed to verify the impact of refrigerator use on household food waste carbon footprint:

$$Y_{it} = \beta_0 + \beta_1 RU_{it} + \sum k_{it} Z_{it} + \varepsilon_{it} \quad (2)$$

TABLE 2 The definition and statistical analysis of variables.

Variable	Definition	Mean	St. Dev.	Min	Max
Food waste carbon footprint	Logarized food waste by type and its carbon footprint factor multiplied and summed (g CO2eq)	3.36	2.80	0	9.30
RU	Whether having a refrigerator (1 = yes, 0 = no)	0.64	0.48	0	1
Gender	1 = male,0 = female	0.81	0.39	0	1
Age	Age recorded on the day of the survey (years)	55.71	12.97	19	94
Education	1 = Elementary school and below, 2 = Middle school, 3 = High school or Technical secondary school, 4 = Junior college and above	1.87	0.90	1	4
Ethnicity	1 = Han, 0 = minority	0.87	0.33	0	1
Work status	Whether working (1 = yes, 0 = no)	0.60	0.49	0	1
Dietary Preferences	Mean food preference score of household members	1.68	0.52	0.01	4.05
Dietary Knowledge	Average dietary knowledge score of household members	3.33	0.44	1.66	5.18
Proportion of families eating out	Number of meals eaten away from home/total number of meals eaten over 3 days (%)	9.17	20.07	0	100
Family economic condition	Household income per capita (yuan, log)	8.70	1.50	0	12.61
Household size	Total number of family members (persons)	3.32	1.54	1	13
Age 14	Proportion of family members aged 14 years and less (%)	9.71	16.88	0	100
Age 60	Proportion of family members aged 60 years and older (%)	27.76	39.26	0	100
Family BIM	Household weighted BMI by age/household size (BMI = weight[kg]/square of height [meter])	21.97	3.86	2.19	40.20
Community development	Community development score	1.89	0.71	0.62	3.35
North-south region	1 = south, 0 = north	0.57	0.50	0	1
Urban-rural type	1 = urban, 0 = rural	0.32	0.47	0	1

Where Y_{it} is the explanatory variable food waste carbon footprint. RU_{it} is household refrigerator use. Z_{it} is the control variable. β_0, β_1, k_{it} is the coefficient of the variable. ε_{it} is the random error term. The i and t are the head of the household's *id* and year, respectively. This paper verifies the effect of refrigerator use on household food waste carbon footprint through Equation 2.

In terms of specific model selection, due to the fact that the carbon footprint of food waste contains censored data, this paper uses the Tobit regression model (IEA, 2022) to carry out the empirical analysis.

3 Empirical results and analysis

3.1 Descriptive analysis

In order to visualize the connection between household refrigerator use and residents' household food waste carbon footprint, a simple comparative analysis of household food waste carbon footprint by category is first conducted, as shown in Figure 2. It is not difficult to find that household refrigerator use will significantly reduce the household food waste carbon footprint for cereal-based and vegetable-based foods. However, it is the opposite result for meat, egg and dairy products and aquatic products. This may be related to advances in storage technology encouraging households to stock up on more price-elastic foods, thus generating more food waste (Moult et al., 2018). Therefore, it remains to be verified whether household refrigerator use is beneficial in reducing the carbon footprint of food waste.

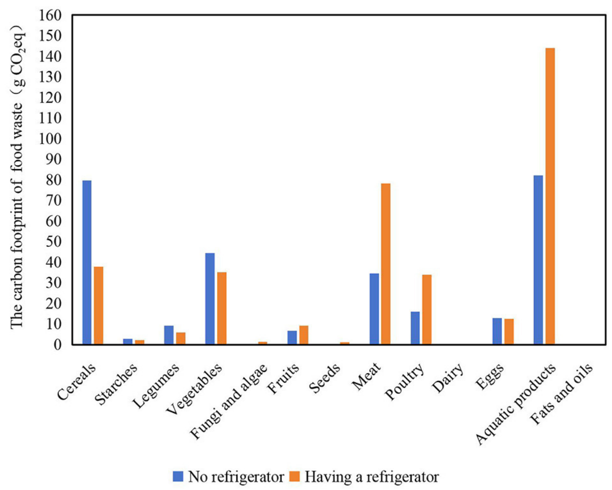

FIGURE 2
Descriptive analysis.

3.2 Benchmark regression

According to Equation 2, a regression analysis was conducted to gradually investigate the impact of refrigerator use on the carbon footprint of food waste using Stata17 software. The results show (Table 3) that, in the case of Column (4), refrigerator use significantly and negatively affects the household's carbon footprint of food waste when controlling for as many of the other factors affecting the carbon footprint of food waste as possible (Min et al., 2021). Regarding the control variables, household head-level age, education, ethnicity, and dietary preferences significantly affect the food waste carbon footprint. Specifically, the age and education level of the household head and the ethnicity to which he or she belongs negatively affect the food waste carbon footprint. In other words, the older the age, the higher the education level, the smaller the value of food waste carbon footprint. Han Chinese households have smaller food waste carbon footprints relative to ethnic minority households. The possible explanation for this is that the older and the more educated households and Han Chinese households have more food cooking knowledge and less food waste, which corresponds to a smaller food waste carbon footprint value. This is contradictory but not conflicting with Ananda et al. (2022). The data in this paper covers 9 provinces in China, which is more representative. The dietary preference of the household head significantly and positively affect the carbon footprint of food waste, which is consistent with the study of Thiel et al. (2021). The possible explanation is that higher dietary preference score favors healthier dietary consumption, with more meals at home and correspondingly larger household food waste carbon footprint value. Per capita income level and population size and percentage of adolescents at the household level, and development index at the community level significantly and positively affect the food waste carbon footprint. The higher the per capita income level, the higher the consumption level and quality of life, the more serious the food waste phenomenon is, which is consistent with the result of Song et al. (2015) on household food waste in China. Large-scale households with more daily meal preparation have a larger carbon footprint of food waste. The higher the proportion of adolescents among household members, the more food safety and health conscious they are, the larger the carbon footprint of food waste is likely to be. This enriches the study of Smith and Landry (2021). The higher the level of community development and the more diversified the food supply orientation, the higher the potential for food waste (Smith and Landry, 2021).

TABLE 3 Refrigerator use and the carbon footprint of food waste.

Variable	Food waste carbon footprint			
	(1)	(2)	(3)	(4)
RU	−0.128 (0.169)	−0.104 (0.176)	−0.500*** (0.181)	−0.385** (0.182)
Gender	0.078 (0.199)	−0.088 (0.204)	0.072 (0.203)	0.099 (0.202)
Age	−0.011 (0.007)	−0.019** (0.010)	−0.026*** (0.010)	−0.027*** (0.010)
Education	−0.196** (0.090)	−0.054 (0.093)	−0.266*** (0.096)	−0.215** (0.096)
Ethnicity	−0.762*** (0.229)	−0.626*** (0.228)	−0.852*** (0.228)	−0.726*** (0.228)
Work status	−0.070 (0.190)	−0.094 (0.195)	0.298 (0.199)	0.274 (0.200)
Dietary preferences	0.399*** (0.146)	0.400*** (0.147)	0.365** (0.145)	0.345** (0.144)
Proportion of families eating out		−0.027*** (0.004)	−0.031*** (0.004)	−0.035*** (0.004)
Family economic condition		0.139** (0.059)	0.109* (0.059)	0.110* (0.058)
Household size		0.329*** (0.061)	0.385*** (0.061)	0.326*** (0.062)
Age 14		0.014** (0.007)	0.013* (0.007)	0.015** (0.007)
Age 60		0.006** (0.003)	0.007** (0.003)	0.007** (0.003)
Family BIM		−0.013 (0.027)	−0.010 (0.027)	0.016 (0.027)
Community development			1.047*** (0.130)	0.912*** (0.137)
North-south region				0.883*** (0.161)
Urban–rural type				−0.072 (0.173)
Constant	3.397*** (0.679)	1.568 (1.059)	0.450 (1.057)	−0.251 (1.060)
Pseudo R^2	0.002	0.010	0.014	0.016
N	3,570	3,453	3,453	3,453

Standard errors in parentheses; significance level $^{*}p < 0.10$, $^{**}p < 0.05$ and $^{***}p < 0.01$.

3.3 Robust test

3.3.1 Replacement of food waste carbon footprint indicator

In order to verify the robustness of the above estimation results, this paper uses the carbon footprint of commonly used household food waste as the explanatory variable. Among them, the selection of commonly used food categories refers to Thapa et al. (2022), including cereals, vegetables and meat, eggs and dairy foods. At this time, household food waste carbon footprint = household cereals food waste * carbon footprint coefficient + vegetables food waste * carbon footprint coefficient + meat, eggs and milk food waste * carbon footprint coefficient. The results of the stepwise fitting regression are shown in Table 4, where refrigerator use significantly negatively affects the food waste carbon footprint, which is consistent with the baseline regression results.

3.3.2 PSM regression for overcoming selectivity bias

The endogeneity problem arises due to the presence of self-selection bias of the respondents, which makes it possible that household ownership of refrigerators may not be a random phenomenon. In this section, the propensity score matching (PSM)

TABLE 4 Robustness tests I: replacing explained variable.

Variable	Food waste carbon footprint			
	(1)	(2)	(3)	(4)
RU	−0.307* (0.164)	−0.277 (0.170)	−0.625*** (0.176)	−0.481*** (0.176)
Control variables	Yes	Yes	Yes	Yes
Pseudo R^2	0.002	0.012	0.015	0.019
N	3,583	3,453	3,453	3,453

Standard errors in parentheses; significance level $^*p < 0.10$, $^{**}p < 0.05$ and $^{***}p < 0.01$.

TABLE 5 Robustness tests II: based on the PSM model.

	Food waste carbon footprint			
	Matching method	Average treatment effect (ATT)	St. Dev.	T-statistic
RU	Nearest neighbor (1:1)	−0.501**	0.222	−2.26
	Nearest neighbor (1:4)	−0.396**	0.192	−2.06
	Radius	−0.109	0.068	−1.61
	Kernel	−0.381**	0.173	−2.20
N	3,453			

$^{***}p < 0.01$ ($t > 2.58$), $^{**}p < 0.05$ ($t > 1.96$), $^*p < 0.1$ ($t > 1.65$).

TABLE 6 Heterogeneity analysis: gender, and education levels.

Variable	Food waste carbon footprint			
	Male	Female	Whether education levels ≥mean	
			<mean	≥mean
RU	−0.488** (0.201)	0.334 (0.430)	0.126 (0.247)	−0.882*** (0.262)
Control variables	Yes	Yes	Yes	Yes
Pseudo R^2	0.018	0.016	0.016	0.019
N	2,810	643	1,356	2,100

Standard errors in parentheses; significance level $^*p < 0.10$, $^{**}p < 0.05$ and $^{***}p < 0.01$.

method is used to fit the regression, and the nearest neighbor matching, radius matching and kernel matching methods are chosen to conduct the study to verify the food waste carbon footprint effect of refrigerator use. The ATT values, standard deviations and t-statistics of the samples after matching are given in Table 5. The analysis reveals that the average treatment effect coefficients are all negative and the T-statistics are basically greater than 1.65, indicating that refrigerator use still significantly and negatively affects the food waste carbon footprint after sample matching.

3.4 Heterogeneity analysis

China is a vast country with large geographic and cultural differences. In order to identify the heterogeneous impact of refrigerator use on the carbon footprint of food waste, this paper draws on existing studies (Ananda et al., 2022; Smith and Landry, 2021; Tilman and Clark, 2014) and carries out a comparative subgroup analysis from the perspectives of gender and education level of the head of the household, household economic level, and the urban-rural types.

3.4.1 Gender and education level of the household head

It has been shown that female heads of household exhibit completely different characteristics from men in their food discarding decisions and have higher food waste rates due to nutritional balance considerations in family meals (Smith and Landry, 2021; Tonini et al., 2018). A higher food waste rate implies a larger food waste carbon footprint value. This subsection compares and analyzes the data by gender grouping (Table 6). In order to investigate the economic significance of refrigerator use on the reduction of food waste carbon footprint for each group, the marginal transformation of regression coefficients is reported below. The gender-based analysis finds that gender differences make a significant difference in the impact of refrigerator use on the carbon footprint of food waste, while other variables remain the same. When a household purchases a refrigerator, the carbon footprint of food waste decreases by 0.49 percentage points for male-headed households and increases by 0.33 percentage points for female-headed households. It is significant in terms of focusing on "Love Food, Save Food" campaign for the female population.

Differences in education levels affect food discarding decisions, resulting in different food waste carbon footprints. Referring to Smith and Landry (2021) and Usubiaga et al. (2018), this paper conducts a group comparison analysis according to whether it is greater than or equal to the mean (Table 6). It is found that the effect of refrigerator use on food waste carbon footprint for the group whose household head's education level is junior high school and above exhibits a significant negativity, and that the refrigerator use will make the food waste carbon footprint decrease by 0.88 percentage points. It implies that improving the education level of household decision makers is significant in reducing food system GHG emissions.

3.4.2 Comparative analysis of household income and urban-rural type

Given the different effects of differences in household income levels on food waste and their carbon footprints (Ananda et al., 2022; Smith and Landry, 2021; Song et al., 2015; Tonini et al., 2018), this paper measures the marginal effect of refrigerator use on the carbon footprint of food waste by grouping households according to whether their income is greater than or equal to the average income (Table 7). The findings reveal that the food waste carbon footprint effect of refrigerator use is more significant in high-income households. When the income level is higher, the diet structure is more diversified and the food

TABLE 7 Heterogeneity analysis: household income and urban-rural type.

Variable	Food waste carbon footprint			
	Low-income households	High-income households	Urban	Rural
RU	−0.116 (0.246)	−0.676** (0.263)	−0.082 (0.363)	−0.384* (0.209)
Control variables	Yes	Yes	Yes	Yes
Pseudo R^2	0.025	0.015	0.014	0.022
N	1,273	2,192	1,281	2,172

Standard errors in parentheses; significance level $^{*}p < 0.10$, $^{**}p < 0.05$ and $^{***}p < 0.01$.

TABLE 8 Refrigerator use, dietary knowledge and the carbon footprint of food waste.

Variable	Food waste carbon footprint			
	(1)	(2)	(3)	(4)
RU	−0.385** (0.182)		−0.338* (0.189)	−2.476** (1.244)
Dietary knowledge		−0.444** (0.181)	−0.431** (0.181)	−0.860*** (0.306)
RU*Dietary knowledge				0.650* (0.374)
Control variables	Yes	Yes	Yes	Yes
Pseudo R^2	0.016	0.016	0.016	0.017
N	3,453	3,240	3,240	3,240

Standard errors in parentheses; significance level $^{*}p < 0.10$, $^{**}p < 0.05$ and $^{***}p < 0.01$.

surplus is reduced (Usubiaga et al., 2018). The food waste carbon footprint of household refrigerator use decreases by 0.68% points. Comparatively speaking, the decrease in the carbon footprint of food waste caused by the use of refrigerators in low-income households is not significant.

There are obvious differences in the dietary structure of urban and rural residents (Ananda et al., 2022). According to the urban and rural household grouping (Table 7), the average marginal effect of refrigerator use is measured. It is found that the use of refrigerators in rural households has a significantly negative impact on the carbon footprint of food waste, resulting in a decrease of 0.38 percentage points. The possible explanation for this is that rural households are larger in size and have more food preparation and surplus than urban households. If the refrigerator's food storage function can be fully utilized, it will effectively reduce the carbon footprint of food waste.

4 Discussion

4.1 Welfare effects of reducing the carbon footprint of food waste

The results of the study show that the carbon footprint of household food waste can be significantly reduced through improving storage technologies, namely the use of domestic refrigerators. Reducing the carbon footprint of food waste has multiple environmental, economic and social benefits.

On the one hand, household refrigerators can reduce food waste by slowing down food spoilage, thereby reducing greenhouse gas emissions and minimizing negative impacts on the environment. At the same time, less food waste means more efficient use of resources, which can reduce the consumption of water, soil, and energy resources used in the food production process, which is conducive to environmental sustainability (Aschemann-Witzel, 2016). On the other hand, the use of household refrigerators mitigates the monetary loss of household food purchases by effectively curbing potential wasteful behaviors, which ultimately improves consumers' economic welfare (Walmsley et al., 2015). In addition, the reduction in food waste due to refrigerator use can help address food shortages and hunger, thus improving social equity and sustainability. By reducing food waste and donating surplus food to charitable organizations (Wang et al., 2023), the availability of food can be increased. The number of hungry people can be reduced. Social equity can be improved to promote harmonious social development.

4.2 Moderating effect of dietary knowledge on refrigerator use affecting food waste behavior

Research has shown that greater dietary knowledge and adherence to dietary guidelines are associated with less household food waste (Willett et al., 2019). China is a vast country, and the level of dietary knowledge varies greatly among households (Smith and Landry, 2021). Only those households with higher levels of dietary knowledge can effectively utilize the home refrigerator to store food, thus reducing food waste and its carbon footprint (Xu et al., 2020). In contrast, those households with low dietary knowledge, even if they have a refrigerator, have limited food savings due to irrational use. Increasing consumers' knowledge of how to prepare and store food would be one of the practical solutions to reduce the carbon footprint of food waste (Yu and Jaenicke, 2020).

In order to verify whether the level of dietary knowledge plays a moderating role in the effect of refrigerator use on the carbon footprint of food waste, and with reference to the Smith and Landry (2021) study, this section introduces a fitted regression with the cross terms of refrigerator use and dietary knowledge scores (composite scores based on the scores of respondents in the Dietary Nutrition Questionnaire, computed by utilizing entropy method). Table 8 presents the estimation results by step, including variables for refrigerator use, dietary knowledge, and their cross terms. The results show that the interaction term between refrigerator use and dietary knowledge affects the carbon footprint of food waste, which implies that dietary knowledge does have a moderating role in the process of refrigerator use affecting the carbon footprint of food waste.

Specifically, the last column (4) shows that the average marginal effect of refrigerator use (−2.476 + 0.650*dietary knowledge) varies with the magnitude of the dietary knowledge index (Equation 3).

$$\textit{Marginal effect of refrigerator use} = \begin{cases} > 0 \text{ if } \textit{Dietary knowledge} > 3.809 \\ = 0 \text{ if } \textit{Dietary knowledge} = 3.809 \\ < 0 \text{ if } \textit{Dietary knowledge} < 3.809 \end{cases} \quad (3)$$

It is calculated that refrigerator use reduces food waste carbon footprint when household members' dietary knowledge index is less than 3.809. The refrigerator use instead increases food waste carbon footprint when household members' dietary knowledge index is greater than 3.809. Therefore, the level of dietary knowledge plays a bidirectional moderating role in the effect of refrigerator use on food waste carbon footprint, enriching the study of Xu et al. (2020) that refrigerator use reduces food waste carbon footprint.

5 Conclusions and implications

Based on the China Health and Nutrition (CHNS) database and the China Food Life Cycle Assessment Database (CFLCAD), this paper investigates the association between refrigerator use and food waste carbon footprint in urban and rural households in China. Statistical characterization reveals that household refrigerator use will significantly reduce the carbon footprint of food waste for cereals and vegetables, but it was the opposite result for meat, eggs and milk. Therefore, the effect of refrigerator use on the overall carbon footprint of food waste has yet to be verified. The results of the analysis show that: (1) Refrigerator use significantly reduces food waste carbon footprint. (2) The extent to which refrigerator use reduces the carbon footprint of food waste varies according to the gender and education level of the household head, household per capita income level and urban-rural type. (3) Dietary knowledge plays a moderating role in how refrigerator use affects the carbon footprint of food waste.

Reducing food waste is a complex economic, social and environmental issue (Zheng et al., 2023). Multiple measures should be taken to reduce food waste and achieve the goal of "energy saving and emission reduction." Based on the above research, it is not difficult to draw the following insights.

Firstly, promote the "refrigerator trade-in" and the "refrigerator technology revolution." Research has found that appropriate refrigerator temperature and efficiency are conducive to food storage and reducing the carbon footprint of food waste. Generally speaking, the use cycle of refrigerators is 10–15 years. The year of the data survey in this paper is nearly a decade away, so families with existing refrigerators need to purchase new ones. The state should do a good job of exchanging old refrigerators for new ones. Families without refrigerators can also receive home appliance subsidies to encourage the purchase of refrigerators, collectively contributing to the reduction of food waste.

Secondly, popularize food nutrition education and promote "Love Food, Reduce Waste." Given the heterogeneity of the impact of refrigerator use on the carbon footprint of food waste among different groups, emphasis should be placed on those with higher levels of education and per capita income. Targeted publicity on food storage and nutritional knowledge to reduce the carbon footprint of food waste among the highly educated and high-income groups would be of greater significance in reducing greenhouse gas emissions from the food system.

Finally, improving residents' dietary knowledge can promote healthy eating habits among them. Improving residents' dietary knowledge to a certain extent can prompt them to pay attention to dietary nutritional combinations, change their daily diets from meaty to balanced nutrition, reduce excessive consumption of meat, eggs and dairy foods and make rational use of the refrigerator's function of storing food. This can help reduce food waste and its carbon footprint.

It should be noted that there are two important potential limitations of this study. Firstly, some of the research data on the carbon footprint of household food waste of Chinese residents are not novel enough. Household food waste surveys are time-consuming and laborious. Data collection is difficult. The existing household-level food waste databases are very limited. The accessible CHNS database collectes household-level food waste data, but the food waste data are not published in 2015 or later, making the data in this study obsolete, which may not accurately reflect the current status of household food waste and its carbon footprint in China. However, the perspective of this paper is the impact of refrigerator use on the carbon footprint of food waste, and given the millennia-old tradition of food waste and the current situation of household refrigerator use, it is expected that this study can still provide credible and contemporary conclusions. Secondly, the CHNS database directly considers the quantity of the food wasted by a household over 3 days at home as its total food waste without categorizing the avoidable and unavoidable food wasted by the household. Generally speaking, inedible parts (e.g., vegetable peelings, soya bean dregs and bones) are unavoidable food waste and should not be included in food waste statistics according to FAO. The CHNS database counts various indicators of household health and nutrition in China. The survey on household food waste is only one of them, which is insufficiently detailed and lacks of further categorization of food waste. This may have magnified the actual amount of food waste in Chinese households, and at the same time, it does not help to focus on how to reduce avoidable food waste and its carbon footprint.

In our future study, we will continue to focus on the theme of the carbon footprint of household food waste in China and aim to conduct an independent questionnaire survey to obtain real-time data on household food waste and its carbon footprint. At the same time, we will optimize the design of the questionnaire in the CHNS database to differentiate between avoidable and unavoidable household food waste. Based on this, we will explore the factors affecting household food waste and its carbon footprint and make recommendations for improvement.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: The datasets analyzed in this research were available in the Carolina Population Center of the University of North Carolina. All materials were public and could be found on http://www.cpc.unc.edu/projects/china. This research accessed the data on 10 September 2023.

Author contributions

LZ: Data curation, Formal analysis, Validation, Writing – original draft. LY: Conceptualization, Supervision, Writing – review & editing. LQ: Methodology, Supervision, Writing – review & editing. JH: Conceptualization, Methodology, Supervision, Writing – review & editing. XZ: Supervision, Writing – review & editing. YL: Conceptualization, Methodology, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. The authors thank National Social Science Foundation of China (Project No. 19ZDA116), the National Natural Science Foundation of China (Project No. 72273061), the Youth Program of Social Science Foundation of Jiangsu Province (Project No. 22GLC015), the Research and Practice Innovation Program for Graduate Students in Jiangsu Province (Project No. KYCX24_1951), and the Special Program for Doctoral Talents Serving the Special Needs of the State at Nanjing University of Finance and Economics (Project No. BSZX2023-09) for their financial support.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

References

Adelodun, B., Kim, S. H., Odey, G., and Choi, K. (2021). Assessment of environmental and economic aspects of household food waste using a new environmental-economic footprint (EN-EC) index: a case study of Daegu, South Korea. *Sci. Total Environ.* 776:145928. doi: 10.1016/j.scitotenv.2021.145928

Ananda, J., Gayana Karunasena, G., and Pearson, D. (2022). Identifying interventions to reduce household food waste based on food categories. *Food Policy* 111:102324. doi: 10.1016/j.foodpol.2022.102324

Aschemann-Witzel, J. (2016). Waste not, want not, emit less. *Science* 352, 408–409. doi: 10.1126/science.aaf2978

Berjan, S., Vaško, Ž., Ben Hassen, T., El Bilali, H., Allahyari, M. S., Tomić, V., et al. (2022). Assessment of household food waste management during the COVID-19 pandemic in Serbia: a cross-sectional online survey. *Environ. Sci. Pollut. Res.* 29, 11130–11141. doi: 10.1007/s11356-021-16485-8

Boehm, R., Wilde, P. E., Ver Ploeg, M., Costello, C., and Cash, S. B. A. (2018). Comprehensive life cycle assessment of greenhouse gas emissions from U.S. household food choices. *Food Policy.* 79, 67–76. doi: 10.1016/j.foodpol.2018.05.004

Bolwig, S., Tanner, A. N., Riemann, P., and Redlingshofer, B. (2021). *Reducing Consumer Food Waste Using Green and Digital Technologies*. United Nations Environment Programme; United Nations Environment Programme Technical University of Denmark Partnership.

Brancoli, P., Rousta, K., and Bolton, K. (2017). Life cycle assessment of supermarket food waste. *Resourc. Conserv. Recycl.* 118, 39–46. doi: 10.1016/j.resconrec.2016.11.024

Brown, T., Hipps, N. A., Easteal, S., Parry, A., and Evans, J. A. (2014). Reducing domestic food waste by lowering home refrigerator temperatures. *Int. J. Refrigeration.* 40, 246–253. doi: 10.1016/j.ijrefrig.2013.11.021

Cai, H., Biesbroek, S., Wen, X., and Fan, S. (2022). Environmental footprints of Chinese foods and beverages: literature-based construction of a LCA database. *Data Brief.* 42:108244. doi: 10.1016/j.dib.2022.108244

Cheng, S., Song, G., Yang, D., Yao, L., Jiang, Z., Zhao, M., et al. (2022). Spatial–temporal and structural differences in the carbon footprints embedded in households food waste in urban and rural China. *Environ. Sci. Pollut. Res.* 30, 35009–35022. doi: 10.1007/s11356-022-24664-4

Conrad, Z., Niles, M. T., Neher, D. A., Roy, E. D., Tichenor, N. E., Jahns, L., et al. (2018). Relationship between food waste, diet quality, and environmental sustainability. Marelli B, editor. *PLoS ONE.* 13:e0195405. doi: 10.1371/journal.pone.0195405

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., Leip, A., et al. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food.* 2, 198–209. doi: 10.1038/s43016-021-00225-9

Čuček, L., Klemeš, J. J., and Kravanja, Z. A. (2012). Review of footprint analysis tools for monitoring impacts on sustainability. *J. Clean. Prod.* 34, 9–20. doi: 10.1016/j.jclepro.2012.02.036

Davenport, M. L., Qi, D., and Roe, B. E. (2019). Food-related routines, product characteristics, and household food waste in the United States: a refrigerator-based pilot study. *Resourc. Conserv. Recycl.* 150:104440. doi: 10.1016/j.resconrec.2019.104440

Ding, Y., Min, S., Wang, X., and Yu, X. (2022). Memory of famine: the persistent impact of famine experience on food waste behavior. *China Econ. Rev.* 73:101795. doi: 10.1016/j.chieco.2022.101795

Eberle, U., and Fels, J. (2016). Environmental impacts of German food consumption and food losses. *Int. J. Life Cycle Assess.* 21, 759–772. doi: 10.1007/s11367-015-0983-7

Ellison, B., and Lusk, J. L. (2018). Examining household food waste decisions: a vignette approach. *Appl. Eco. Perspect. Pol.* 40, 613–631. doi: 10.1093/aepp/ppx059

Eriksson, M., Strid, I., and Hansson, P. (2015). Carbon footprint of food waste management options in the waste hierarchy – a Swedish case study. *J. Clean. Prod.* 93, 115–125. doi: 10.1016/j.jclepro.2015.01.026

European Commission (2018). *Joint Research Centre. Best Environmental Management Practice for the Waste Management Sector: Learning from Frontrunners.* LU: Publications Office. Available at: https://data.europa.eu/doi/10.2760/50247

Fami, H. S., Aramyan, L. H., Sijtsema, S. J., and Alambaigi, A. (2019). Determinants of household food waste behavior in Tehran city: a structural model. *Resourc. Conserv. Recycl.* 143, 154–166. doi: 10.1016/j.resconrec.2018.12.033

FAO (2019). *Moving Forward on Food Loss and Waste Reduction*. Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/3/ca6~030en/ca6030en.pdf

Finkbeiner, M. (2009). Carbon footprinting—opportunities and threats. *Int. J. Life Cycle Assess.* 14, 91–94. doi: 10.1007/s11367-009-0064-x

Giordano, C., and Franco, S. (2021). Household food waste from an international perspective. *Sustainability* 13:5122. doi: 10.3390/su13095122

Gooch, M., Matsubuchi-Shaw, M., Bucknell, D., LaPlain, D., and Kohler, L. (2022). Quantifying the carbon footprint of household food waste and associated GHGs in

Oakville, Ontario, and a municipality's role in reducing both food waste and GHGs. *Canad. Geographer*. 66, 769–782. doi: 10.1111/cag.12794

Grant, F., and Rossi, L. (2022). Sustainable choices: the relationship between adherence to the dietary guidelines and food waste behaviors in Italian families. *Front. Nutr*. 9:1026829. doi: 10.3389/fnut.2022.1026829

Gustavsson, J., Cederberg, C., Sonesson, U., and Emanuelsson, A. (2013). The methodology of the FAO study: global food losses and food waste-extent, causes and prevention. *Swedish Institute Food Biotechnol*. 2013:70.

Hamilton, S. F., and Richards, T. J. (2019). Food policy and household food waste. *Am. J. Agri. Econo*. 101, 600–614. doi: 10.1093/ajae/aay109

Holsteijn, F. V., and Kemna, R. (2018). Minimizing food waste by improving storage conditions in household refrigeration. *Resourc. Conserv. Recycl*. 128, 25–31. doi: 10.1016/j.resconrec.2017.09.012

IEA, (2022). *CO2 Emissions in 2022*. Available at: https://www.iea.org/reports/co2-emissions-in-2022 (accessed 29 June 2023).

Lauk, C., Kaufmann, L., Theurl, M. C., Wittmann, F., Eder, M., Hörtenhuber, S., et al. (2022). Demand side options to reduce greenhouse gas emissions and the land footprint of urban food systems: a scenario analysis for the City of Vienna. *J. Clean. Prod*. 359:132064. doi: 10.1016/j.jclepro.2022.132064

Lee, J., Taherzadeh, O., and Kanemoto, K. (2021). The scale and drivers of carbon footprints in households, cities and regions across India. *Glob. Environ. Change* 66:102205. doi: 10.1016/j.gloenvcha.2020.102205

Li, Y., Wang, L., Liu, G., and Cheng, S. (2021). Rural household food waste characteristics and driving factors in China. *Resourc. Conserv. Recycl*. 164:105209. doi: 10.1016/j.resconrec.2020.105209

Liu, C., Shang, J., and Liu, C. (2023). Exploring household food waste reduction for carbon footprint mitigation: a case study in Shanghai, China. *Foods* 12:3211. doi: 10.3390/foods12173211

Liu, L., Zhang, L., Li, B., Wang, Y., and Wang, M. (2024). Can financial agglomeration curb carbon emissions reduction from agricultural sector in China? Analyzing the role of industrial structure and digital finance. *J. Clean. Prod*. 440:140862. doi: 10.1016/j.jclepro.2024.140862

Min, S., Wang, X., and Yu, X. (2021). Does dietary knowledge affect household food waste in the developing economy of China? *Food Policy* 98:101896. doi: 10.1016/j.foodpol.2020.101896

Moult, J. A., Allan, S. R., Hewitt, C. N., and Berners-Lee, M. (2018). Greenhouse gas emissions of food waste disposal options for UK retailers. *Food Policy* 77, 50–58. doi: 10.1016/j.foodpol.2018.04.003

Ponis, S. T., Papanikolaou, P.-., A., Katimertzoglou, P., and Ntalla, A. C. (2017). Household food waste in Greece: a questionnaire survey. *J. Clean. Prod*. 149, 1268–1277. doi: 10.1016/j.jclepro.2017.02.165

Qi, D., Apolzan, J. W., Li, R., and Roe, B. E. (2020). Unpacking the decline in food waste measured in Chinese households from 1991 to 2009. *Resourc. Conserv. Recycl*. 160:104893. doi: 10.1016/j.resconrec.2020.104893

Qi, D., and Roe, B. E. (2016). Household food waste: multivariate regression and principal components analyses of awareness and attitudes among U.S. consumers. Van Rijnsoever F, editor. *PLoS ONE* 11:e0159250. doi: 10.1371/journal.pone.0159250

Qian, L., Li, F., Liu, H., and Wang, L. (2022a). Are the slimmer more wasteful? The correlation between body mass index and food wastage among Chinese youth. *Sustainability* 14:1411. doi: 10.3390/su14031411

Qian, L., Rao, Q., Liu, H., McCarthy, B., Liu, L. X., Wang, L., et al. (2022b). Food waste and associated carbon footprint: evidence from Chinese universities. *Ecosyst. Health Sustain*. 8:2130094. doi: 10.1080/20964129.2022.2130094

Quested, T., and Parry, A. (2017). Household Food Waste in the UK, 2015 (WRAP Report).

Rasines, L., Castillejo, N., San Miguel, G., and Aguayo, E. (2023). Can household storage conditions reduce food waste and environmental impact? A broccoli case study. *Sci. Total Environ*. 892:164779. doi: 10.1016/j.scitotenv.2023.164779

Scholz, K., Eriksson, M., and Strid, I. (2015). Carbon footprint of supermarket food waste. *Resourc. Conserv. Recycl*. 94, 56–65. doi: 10.1016/j.resconrec.2014.11.016

Scialabba, N. (2015). *Food wastage footprint and Climate Change. Food and Agriculture Organization of the United Nations*. Available at: https://openknowledge.fao.org/handle/20.500.14283/BB144e

Secondi, L., Principato, L., and Laureti, T. (2015). Household food waste behaviour in EU-27 countries: a multilevel analysis. *Food Policy* 56, 25–40. doi: 10.1016/j.foodpol.2015.07.007

Smith, T. A., and Landry, C. E. (2021). Household food waste and inefficiencies in food production. *Am. J. Agri. Econ*. 103, 4–21. doi: 10.1111/ajae.12145

Song, G., Li, M., Semakula, H. M., and Zhang, S. (2015). Food consumption and waste and the embedded carbon, water and ecological footprints of households in China. *Sci. Total Environ*. 529, 191–197. doi: 10.1016/j.scitotenv.2015.05.068

Thapa, P., Hasnine, M. T., Zoungrana, A., Thakur, S., and Yuan, Q. (2022). Food waste treatments and the impact of composting on carbon footprint in Canada. *Fermentation* 8:566. doi: 10.3390/fermentation8100566

Thiel, C. L., Park, S., Musicus, A. A., Agins, J., Gan, J., Held, J., et al. (2021). Waste generation and carbon emissions of a hospital kitchen in the US: Potential for waste diversion and carbon reductions. Ravindran B, editor. *PLoS ONE* 16:e0247616. doi: 10.1371/journal.pone.0247616

Tilman, D., and Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature* 515, 518–522. doi: 10.1038/nature13959

Tonini, D., Albizzati, P. F., and Astrup, T. F. (2018). Environmental impacts of food waste: Learnings and challenges from a case study on UK. *Waste Manage*. 76, 744–766. doi: 10.1016/j.wasman.2018.03.032

Usubiaga, A., Butnar, I., and Schepelmann, P. (2018). Wasting food, wasting resources: potential environmental savings through food waste reductions: wasting food, wasting resources. *J. Indust. Ecol*. 22, 574–584. doi: 10.1111/jiec.12695

Walmsley, M. R. W., Liu, X., Varbanov, P. S., and Klemešb, J. J. (2015). Environmental footprint comparison amongst dairy, grain and meat products in California. *Chem. Eng. Transact*. 43, 109–114. doi: 10.3303/CET1543019

Wang, Z., Jiang, J., and Zeng, Q. (2023). The effect of dietary awareness on household food waste. *Waste Manag. Res*. 41, 164–172. doi: 10.1177/0734242X221105435

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

Xu, Z., Zhang, Z., Liu, H., Zhong, F., Bai, J., Cheng, S., et al. (2020). Food-away-from-home plate waste in China: preference for variety and quantity. *Food Policy* 97:101918. doi: 10.1016/j.foodpol.2020.101918

Yu, Y., and Jaenicke, E. C. (2020). Estimating food waste as household production inefficiency. *Am. J. Agri. Econ*. 102, 525–547. doi: 10.1002/ajae.12036

Zheng, H., Chen, K., and Ma, Z. (2023). Interactive effects of social norms and information framing on consumers' willingness of food waste reduction behavior. *J. Retail. Consumer Serv*. 75:103525. doi: 10.1016/j.jretconser.2023.103525