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Young Scientists Summer Program

Obesity/overweight and environmental impacts: Assessment of excessive food intake in China

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Program: BNR, EF
Date: 30/1/2023

This report represents the work completed by the author during the IIASA Young Scientists Summer Program (YSSP) with approval from the YSSP mentor.

It was finished by Zhimin Shi on the 30th of January 2023 and has not been altered or revised since.

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For research funded by an external third party we ask the authors to include the full name of the funder, the title of the project and the grant number, e.g.
The authors gratefully acknowledge funding from the European Research Council for the research project 'Forecasting Societies Adaptive Capacities to Climate Change' (FUTURESOC, FP7 230195).

Abstract

Rapidly rising incomes and increased urbanization are driving global dietary transition in which traditional diets are replaced by diets higher in refined sugars, refined fats, oils and, meat. This is closely related to environmental and human health. Considering the large urban population, distinctive urbanization processes, preference for refined foods, and serious environmental challenges, such trends are particularly important for China. Currently, 6.4% of Chinese adults are obese and 34.3% are overweight, which means China became a country with the highest number of obese and overweight people in the world. Excess food intake is considered the fundamental cause of obesity and overweight. At the same time, excessive food intake and unsustainable diet structure will expand the burden on the natural environment and climate change, as well as threaten food security. The environmental impacts of diet patterns and the health consequences of unsustainable diets are recognized as global issues, yet the environmental implications of excess food intake have been less well studied. Building on the representative resident survey data from the China Health and Nutrition Survey, this study estimates in detail the excessive food intake based on the human metabolic theory. Then it assesses its environmental impact based on the life cycle assessment. Results showed an excessive intake of nearly 11.70 Mt of food for one year in China, accounting for approximately 2.05% of the total food production in China. The estimated energy, water, carbon and ecological footprints resulting from excessive food intake amounted up to 10.72 Mtce, 300.82×109 m^3, 37.53 Mt CO_2 eq and 522.99×109 m^2, respectively. Thus, excessive food intake and its corresponding environmental impact have exceeded the amount and impact of avoidable household food waste at home in China. Cereals and meats have a dominant role in excessive food intake and related environmental impact. Moreover, significant differences in excess food intake among populations with different demographic characteristics and urbanization levels, reflected that excess food intake and its environmental impacts were higher among people living in rural areas and men. This study provides the first estimate of the environmental cost of excessive food intake in China and highlights the importance of considering it in pathways to simultaneously improve both environmental and human health.

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Acknowledgments

I am always deeply grateful to my IIASA mentors Marta Kozicka and Michael Kuhn for their kind and enthusiastic help and encouragement. Their recognition and tolerance have helped me to realize more possibilities for my future research career and have motivated me to do more meaningful things in my research field.

Thanks also to Tanja Huber and Aleksandra Cofala for organizing and helping and to all 2022 YSSPers. Thank you for being with me for one of the best times of my life.

Finally, I am extremely grateful to IIASA for offering me the opportunity to participate in the YSSP programme. I have so many wonderful days and enjoyed all my time at IIASA. At the same time, many thanks to the support of the National Natural Science Foundation of China.

Obesity/overweight and environmental impacts: Assessment of excessive food intake

1. Introduction

The topic of ensuring food security to feed the growing population whilst reducing our global footprint is by far one of the biggest challenges society faces today (UN, 2016). However, the challenges to ending hunger, food insecurity and all forms of malnutrition keep growing (FAO, 2022). The COVID-19 pandemic and the ongoing war in Ukraine have further highlighted the fragilities in agri-food systems and the inequalities in our societies. At the same time, more frequent and severe extreme climate events are disrupting supply chains, driving further increases in world hunger and severe food insecurity (Fan et al., 2021). The challenge of achieving the Sustainable Development Goals by 2030 is even greater in the face of climate change, natural resource degradation, human health concerns and the global outbreak of uncertainty.

With the increase in global agricultural production capacity, scientific and technological advances and socio-economic development, the progress, that was made during the Millennium Development Goals (MDGs) towards the objective of halving the prevalence of hunger between 1990 and 2015 (Deppermann et al., 2019). The recent declining trends in prevalence of hunger that were observed over the last decades have recently grinded to a halt, and the world is moving backwards in its efforts to end hunger, food insecurity and malnutrition in all its forms (FAO, 2022). The absolute number of people suffering from hunger is increasing again, over 820 million people experience chronic hunger today, while in parallel a worldwide rise in obesity is observed. The world is suffering from bottlenecks in tackling hunger, it is also facing a crisis of deteriorating diet quality.

Despite the fact that hundreds of millions of people still face inadequate food intake, more than 1.9 billion adults worldwide are overweight and more than 650 million residents are obese. The world food supply per capita per day increased from 2893 kcal in 2014 to 2927 kcal in 2018, far exceeding the recommended value of 2533 kcal in the Lancet Report. Meanwhile, the per capita daily fat supply increased from 83.34 g to 86.17 g (FAO, 2020). Low quality or excessive food polarization trend was significant. Such conditions are closely linked to excessive food intake. The relationship between overweight/obese and excessive food intake is bi-directional: on the one hand, excessive food intake is a cause of overweight and obesity; on the other hand, overweight/obese people require a greater food intake to maintain their (increased) basal metabolism.

Facing the uncertainty of future agricultural systems and the burden of feeding a growing population. Scholars and policy makers argue that agricultural productivity should be increased to assure food security in the next decades. Regardless of the feasibility of this technological upgrade due to rising marginal costs, in countries where the rate of overweight and obese people is higher, this strategy is likely to further feed excessive food intake rather than ensuring a more equitable access to food (Franco et al., 2022). In such cases, it is worth studying excessive food intake in-depth, even beyond the health problems related to overweight and obesity, focusing on its environmental impact and on the implications for food production. This is essential for achieving SDG 2 (Zero hunger), SDG 3 (Good health and well-being), SDG 13 (Climate action). In addition, considering excessive food intake and avoiding the problem through effective measures is also part of the global effort to achieve SDG 10 and SDG 12, that is, reducing inequality and carrying out responsible consumption and production.

As one of the food commodity importer and exporters in the world, China has created a miracle of agricultural production by feeding about 21% of the world's population on 8% of the world's arable land, but at the same time, the resources and environmental problems caused in the process are becoming increasingly serious. The carbon footprint of China's food system has nearly doubled in the last 30 years (Lin et al., 2015). As the world's most populous country and one of the most rapidly urbanizing countries, China's food consumption structure is undergoing a major transformation as socio-economic development and living standards increase, with per capita meat consumption increasing from 45.06 kg to 62.43 kg and cereal consumption from 160.75 kg to 193.61 kg per year. Along with this transformation, China has already leaped past the United States to become the country with the largest number of obese and overweight people in the world (Chen, 2015). However, on the other hand, FAO data shows that 134 million people in China are still underfed. China has more difficulty than other countries in reducing the incidence of hunger (FAO, 2015). With this regard, the assessment of excessive food consumption in China is significant from the perspective of food demand and environmental impact.

This research work selects China as a case area to adequately assess the impact of excessive food intake on food demand and environmental health, and expect to provide new ideas and perspectives to address the global food crisis and climate change.

2. Literature review

Considering the relevance of excessive food intake to the environment, some of the recent studies that quantified the environmental impact of the excessive food intake defined it as overconsumption, luxury consumption and unnecessary consumption of food (Blair and Sobal, 2006; Porter and Reay, 2016; Xiong et al., 2020). Based on this consideration, they compared the consumption of each food group with the respective values from the dietary guidelines, defining excessive food intake as the portion of food consumption that exceeds the recommendation, thus accounting for the corresponding environmental impacts. These studies, often using the statistical data of average per capita food consumption, have paved the way for revealing the overall impact of excessive food intake. Conversely, others argued that statistical data and dietary guidelines cannot reflect a realistic picture, because they do not match the nutritional needs of each individual considering the differences in height, age, gender, activity level and so on. These studies prefer to analyze it from a micro perspective, usually based on household- or individual-level survey data (Sundin et al., 2021). They suggested that the definition of excessive food intake should be based on the theory of metabolism, and emphasized that excessive food intake should be considered as metabolic waste as a result of excess body fat accumulated in the population (Toti et al., 2019). Under this definition, the calculation of excessive food intake highlighted energy and food intake beyond what is required to sustain life activities (Franco et al., 2022).

There is increasing evidence that a remarkable amount of food is consumed in excess due to the higher energy demands of obese and overweight individuals (Serafini and Toti, 2016). Focused on the actual physical food intake of the body, Using widespread food consumption to account for excessive food intake appears to be an inappropriate method, due to the food consumption include actual physical food intake and food waste. At the same time, concerned about the time required for the metabolism process and the cumulative effect of excessive food intake on human health, the quantification of excess food intake should focus more on the excess energy requirements of obese and overweight people. Sundin et al. (2021) have accounted for the climate change impacts of excessive food consumption in three typical Swedish diets, and estimated that greenhouse gas emissions from excessive food intake amounted up to 1.2 Mt CO_2e annually, accounting for approximately 2% of the total and 10% of the food-related climate impact in Sweden. Based on 46 food categories composed of the typical Italian diet, (Franco et al., 2022) showed that the total amount of food over-consumed by Italian citizens due to over-nutrition is comparable to the current national assessment of household food waste and that the corresponding environmental impact accounts for 6.15 Mt CO_2e per year. However, similar studies have not been widely carried out in China. Although a great deal of research has been conducted in China over the past few decades on the environmental and health effects of diet. As is widely known for current diet conditions, the intake of some types of food does not meet human nutritional needs, therefore, not all foods should be responsible for excessive food intake and obesity and overweight (Cho et al., 2013). The existing literature does not currently explore the information on which food should be included in the accounting of excessive food intake, nor does it provide an in-depth discussion of excessive food intake and its environmental burden under different demographic characteristics.

3 Materials and methods

3.1 Data sources and sample selection

In this study, dietary and obesity status data were extracted from the China Health and Nutrition Survey (CHNS, http://www.cpc. unc.edu/projects/china), which is supported by an international collaborative project between the Carolina Population Center at the University of North Carolina at Chapel Hill and the National Institute for Nutrition and Health (NINH) at the Chinese Center for Disease Control and Prevention (CCDC). The survey applies a multi-stage, random cluster process to create a representative sample to account for geography, economic status, and other background factors in China (Wang, 2022). To date, 10 rounds of data have been made available, covering the time span from 1989 to 2015. Detailed information on this survey has been introduced in previous studies (Zhai et al., 2014). Currently, the CHNS made the highly informative individual-level survey data available to the public, which has been used in research on food (He et al., 2018; Song et al., 2019). Although the data of CHNS was updated in 2015, the food consumption data was last updated in 2011. Since food consumption was the central focus of the current study, data from 2011 were adopted. Food consumption data originated from Nutrition Surveys, which adopted the method of three consecutive 24-h dietary recall. The three consecutive days during which detailed household food consumption data have been collected were randomly allocated from Monday to Sunday and are almost equally balanced across the seven days of the week for each sampling unit. Socio-economic and anthropometric data for this study were derived from the Adult Survey of CHNS.

Matching respondents' socio-economic characteristics with food consumption data, this study collected complete information on dietary, anthropometric, demographic, socioeconomic, and lifestyle factors of respondents aged 18-75. Respondents who were pregnant, lactating or suffering from cancer, hypertension, diabetes, or cardiovascular disease were excluded because those physical conditions could affect energy intake. Moreover, those with implausible energy intake (i.e., <800 kcal per day or >6000 kcal for males and <600 kcal per day or >4000 kcal for females) (Yu et al., 2016) or extreme height or weight were also not considered in the analysis. After exclusion, 10728 participants were eligible for the study from 2011, including 1330 obese people and 3550 overweight people.

All the food items in the CHNS are recorded with a food code from China Food Composition (Yang et al., 2009). For better comparison with the Chinese Dietary Guidelines, the food items have been aggregated and reclassified into 10 food groups: grains & beans, tubers, vegetables, fruits, meat, aquatic product, eggs, milk, soybeans & nuts and edible oil. The food groups were further refined for accuracy in the calculation of environmental impact. It is worth noting that the measurement of cooking oil may be omitted from the traditional 24-hour recall undertaken in China, due to the specificity of the cooking method and the differences per dish per person (Popkin et al., 2002). Therefore, using national statistical data, this study calibrated the data on edible oil consumption.

2.2 Estimation of the quantity of excessive food intake

In this study, excessive food intake was assumed as the additional caloric intake required to maintain the current condition of an overweight/obese person. Excess energy intake was therefore assessed as the difference between caloric intake at current body weight and caloric intake at normal body weight. Then, excessive food intake can be calculated by allocating the excessive energy intake to each food type with reference to the current diet.

Under this definition, Matching respondents' socio-economic characteristics with food consumption data including at home and dining, this study started with exploring the dietary structure of different populations (normal weight/overweight/obesity group). In this study, food intake and corresponding calorie intake were calculated for each of the three groups. The calorie values per 100g of food intake were obtained from the China Food Composition List (Yang et al., 2009).

To detect overweight and obesity conditions, the widely approved criterion Body Mass Index (BMI), given by the ratio between weight(kg) and square of height (m), was used. Following the criteria recommended by the Working Group on Obesity in China, a person with a BMI between 24 kg·m^{-2} and 27.9 kg·m^{-2} is overweight and over 28 kg·m^{-2} is obese (Chen, 2004).

The individual daily resting energy expenditure (REE, kcal/day) is the minimum amount of energy required to maintain life functions. Based on the Harris-Benedict equation (Harris and Benedict, 1918), REE can be evaluated by gender, age, weight and height for each respondent. Then the total energy expenditure (TEE) is calculated by multiplying resting energy expenditure (REE) and physical activity level (PAL). The basic equations are as follows:

$$REE_m = 66 + 13.7W + 5.0H - 6.8A \quad (1)$$

$$REE_f = 655 + 9.6W + 1.8H - 4.7A \quad (2)$$

$$TEE = REE * PAL, \quad (3)$$

where W is the weight (kg) of each respondent, H is the height (cm), and A is the age (years). PAL refers to the ratio of the total energy consumption of an individual within 24 h to the base metabolic energy consumption of the individual within 24 h. In this study, the PAL coefficient was established by an individual physical activity survey from CHNS. Through Eq. 4-6 proposed by the Institute of Medicine (IOM), the PAL can be calculated (Lupton et al., 2002).

$$\Delta \mathrm{PAL}_{male} = [(\mathrm{a} - 1) \times 1.34 \times \mathrm{t}/1400] \quad (4)$$

$$\Delta \mathrm{PAL}_{female} = [(\mathrm{a} - 1) \times 1.42 \times \mathrm{t}/1400] \quad (5)$$

$$\mathrm{PAL} = 1 + \Delta \mathrm{PAL} \quad (6)$$

Where a is the intensity of a physical activity, which is expressed in metabolic equivalents (METs). t (min) is the time spent performing this activity. The METs values corresponding to the various physical activities are derived from the physical activity summary(Ainsworth et al., 2000).

The excessive energy intake ($\Delta \mathrm{TEE}$) for the population with overweight and obesity can be calculated as the difference between the person's TEE of the state with normal weight and overweight/obesity, as shown in Eq.7.

$$\Delta TEE = TEE_{ob/ow} - TEE_{nor} \quad (7)$$

Where $TEE_{ob/ow}$ is the total energy expenditure of overweight or obesity people, and TEE_{nor} is their corresponding total energy expenditure at normal weight.

Allocating the extra calories to each food according to Chinese eating habits and diet structure, which was investigated at the beginning, the excessive food intake was quantified. It is important to note that in this study we assumed that dietary guidelines across all food types would lead to a benchmark normal weight (for an average person), and the extra calories were provided by food types which were consumed in excess of the recommended dietary guidelines. The conversion rates between the calories consumed in excess by overweight and obese people and the corresponding quantities of food are used to calculate the quantity of each food type corresponding to the excessive caloric intake by the population. Such quantities are then summed up to deliver the total quantity of excessive food intake by people in overweight and obese conditions, and these results were used to estimate the total excessive food intake of overweight and obese people (million kcal/year) in China.

2.3 Environmental impact of excessive food intake

This study aims to analyze the environmental impact associated with excessive food intake. The environmental impacts are reflected by environmental footprint, including energy footprint (EF), carbon footprint (CF), water footprint (WF) and Ecological footprint (EcoF). To account for the EF, CF and WF associated with excessive food intake, the PLCA (Process-based life cycle assessment) model developed in our previous work was adopted (Xiong et al., 2022, 2020). The system boundary consists of the full stages of "farm-to-plate," including agricultural production, processing, distribution, and cooking. The functional unit is defined as 1 kg of food at the point of consumption. For food type *i*, the equations are as follows:

$$ef_i = ef_{i,argriculture} + ef_{i,processing} + ef_{i,distribution} + ef_{i,cooking} \quad (8)$$

$$cf_i = cf_{i,argriculture} + cf_{i,processing} + cf_{i,distribution} + cf_{i,cooking} \quad (9)$$

$$wf_i = wf_{i,argriculture} + wf_{i,processing} + wf_{i,cooking} \quad (10)$$

For plant-based food, the ef, cf and wf from the agricultural production phase are mainly from the production and use of agricultural inputs (such as fertilizers and pesticides), the operation of farm machinery (such as sowing and cultivation), and crop irrigation. The ef, cf and wf of animal food in the agricultural production phase are mainly due to the production of animal feed and the animal feeding process. The ef, cf and wf of the processing stage are mainly due to the primary processing of agricultural products. Examples include the threshing of rice and milling of wheat, the slaughtering of livestock and the sterilization of dairy products.

The environmental footprint of food in the distribution stage is mainly due to the energy consumption and associated greenhouse gases (GHGs) emissions during the storage and transportation of food. The EF of the cooking phase includes the electricity and gas used to cook the food, the WF includes the washing of the food (e.g. rice, vegetables, etc.) and the water used to cook the food, and the CF considers the CO_2 (GHGs) emissions due to cooking energy use. The detailed parameters for emission sources, dataset, and relevant references are introduced in our previous work (Xiong et al., 2022, 2020). The EcoF coefficient refers to (Cai et al., 2022), (Cao and Xie, 2016) and (Cao et al., 2014), who used the input-output method to analyze the input material flow in the life cycle of each unit of food in China, and then converted the material flow into the "global hectare" land use area needed to support its production based on global production and equilibrium factors.

Multiplying the environmental footprint of each food per function unit with its excessive intake, the environmental impact due to excessive food intake of each food can be obtained. Then, the total EF, CF, WF and EcoF of excessive food intake were calculated by Equation 11-14.

$$\mathrm{EF}_t = \sum m_i \times ef_i \quad (11)$$

$$\mathrm{CF}_t = \sum m_i \times cf_i \quad (12)$$

$$\mathrm{WF}_t = \sum m_i \times wf_i \quad (13)$$

$$\mathrm{EcoF}_t = \sum m_i \times ecof_i \quad (14)$$

where EF_t is the total EF and ef_i is the energy footprint per function unit of food item i. Likewise, CF_t, WF_t and EcoF_t are the total CF, WF and EcoF, respectively; cf_i, wf_i and $ecof_i$ are the impacts per function units of food item i, respectively. m_i is the amount of excessive intake of each food.

3. Results

3.1 Dietary structure in Chinese residents

The diet of Chinese residents, including normal weight, overweight and obese groups, is characterized by a high proportion of cereals, vegetables and meats. Cereals account for the largest portion of 36.91%, with 422.78g of daily consumption. Vegetables follow with a percentage of 28.06% and 321.39 daily consumption. Meat makes up nearly 9% of total consumed foods with an average of 107.22 g daily consumption. This is highly consistent with the dietary habits that have been formed in China over thousands of years of agricultural civilization, that is the traditional dietary structure featuring plant-based meals. (Koo, 1976). Regarding energy (calorie intake), cereals, meats and edible oils are the main contributors to energy intake, with an average share of 55.48%, 13.34% and 10.85% respectively. Evidently, carbohydrate-based foods, as well as fat-rich food are still the foundation of providing energy to feed Chinese residents. The current diet exceeds the ceilings of dietary recommendation of Dietary Guidelines for Chinese Residents (Wang et al., 2016) in case of cereals, meats, edible oils and soybeans and nuts. Consumption of tubers, fruits, eggs and dairy products are well below the lower limits of the dietary recommendation. In particular, the consumption of cereals and meat is almost 1.5 times the upper recommended value, while the consumption of fruit is less than half of the lower recommended value. Moreover, the consumption of dairy products is less than one-tenth of the lower recommended value.

The diet of overweight and obese people deviated more from the dietary guidelines than that of normal weight people (Table 1). In particular, consumption of cereals, meats, soybean and nuts and edible oils are above the recommended values. Intake of vegetables, fruits and dairy products are below the recommended values for all groups. This implies that consumption of the foods that exceed dietary guidelines is more likely to be responsible for overweight and obesity.

Table 1. Average daily intake of each food item by Chinese residents

	Group		Cereals	Tubers	Vegetables	Fruits	Meats	Aquatic products	Eggs	Dairy products	Soybeans & nuts	Edible Oils
Consum -ption/g	Chinses resident		422.78	34.39	321.39	80.67	108.36	34.45	30.71	27.41	52.38	32.89
	Recomm-endation	Lower	200	50	300	200	40	40	40	300	25	25
		Upper	300	100	500	350	75	75	50	500	35	30
Calorie /Kcal	Chinses resident		1466.6	72.23	106.05	80.67	367.23	34.45	49.13	16.45	167.76	295.67
	Recomm-endation	Lower	553	105	90	200	124	40	64	180	112.5	225
		Upper	829	210	150	350	232.5	75	80	300	157.5	270

3.2 Excessive energy intake requirements

In general, Chinese residents with obesity and overweight are predominantly engaged in light physical activity daily with their PAL ranging from 1.61-1.75 (National Health Commission of the PRC, 2017). Taking into account the differences in lifestyles between urban and rural residents and the differences in body metabolism levels between men and women, the investigated population were divided into eight groups: rural-obese-male, urban-obese-male, urban-obese-female, rural-obese-female, urban-overweight-male, urban-overweight-female, rural-overweight-male and rural-overweight-female (Fig. 1) For urban residents, the PAL for both obese and overweight people are concentrated at 1.61 and 1.65 for both men and women (Fig. 1(a)). This is probably because there is little difference between the labor participation rates of men and women in urban settings, and social work is the main form of daily activity for urban residents (Li and Zax, 2004). As for rural residents, the activity level of women in the obese and overweight groups is significantly higher than that of men. In the obese group, the PAL for rural women is concentrated in 1.75, which is 0.02 higher than that of rural men; in the overweight group, the difference becomes 0.03. In the course of China's reform and development, the lag in the transfer of rural women to non-agricultural industries has led to a trend towards the feminization of Chinese agriculture, which in turn has affected the physical activity levels of rural women (De Brauw et al., 2008).

On average, the energy intake of obese people exceeded their total daily energy expenditure by 19.29% of, and for overweight people by 5.58% (Fig. 1b). The urban-obese-male and rural-obese-male have the highest average excessive food intake with 470.86 and 556.71 kcal/capita/day, respectively. The urban-overweight-female and rural-overweight female have the lowest excessive food intake with 66.07 and 82.14 kcal/capita/day, respectively. As for other groups, the average excessive food intake range from 124.9 to 334.97, and it shows a trends towards higher male than female and rural than urban. On a population level, excessive energy intake accounts for 39.80 trillion kcal for the Chinese residents with overweight and obesity groups in one year. Significant demographic differences can be detected in this accounting with 20.50% of the total excessive energy intake contributing from rural-obese-male group, and 18.24% coming from urban-obese-male group, in which urban-obese-male and rural-obese-male contribute the most with 18.32% and 20.58%, respectively. Clearly, the excessive energy intake of rural groups is generally higher than the corresponding urban groups. In addition, compared with rural groups, the urban groups present a higher concentrated distribution. The rural-obese-male group has the largest span and the most dispersed distribution.

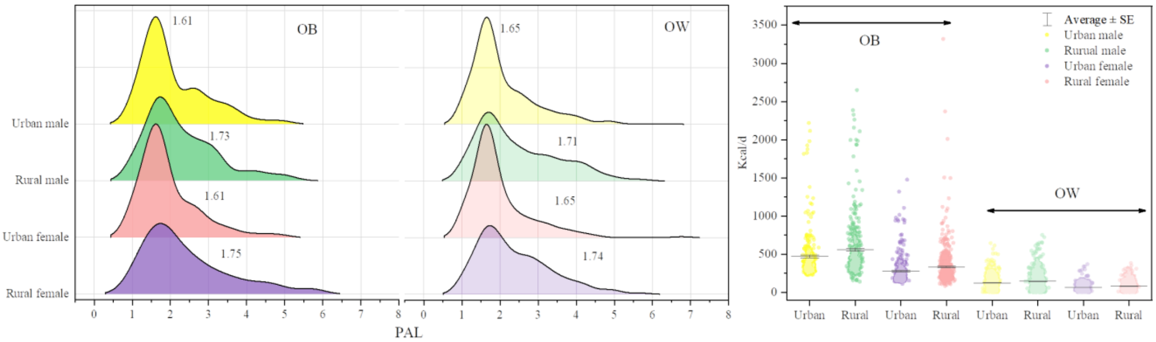

Fig. 1 (a) Physical activity levels and (b) excessive energy intake in obese and overweight groups with different demographic characteristics

3.3 The quantity of excessive food intake

To further quantify the excessive food intake in China, this study allocated the excessive energy intake to different food types. As mentioned above, only those food groups that exceeded the dietary guideline recommendations were considered. It is estimated that nearly 11.70 Mt of food has been excessive intake for one year in China, accounting for nearly 2.05% of the total food production of the country (Fig.2). Food groups contributing most to excessive food intake are rice, wheat and pork, which together make up 89.40% of the total excess food. For different populations, almost 2/3 of total excessive food intake come from the obese group or males, while the rest of 1/3 is comprised of the overweight group or females. On individual level, the average excessive food intake of urban-obese-male, rural-obese-male, urban-obese-female, rural-obese-female, urban-overweight-male, rural-overweight-female, urban-overweight-female and rural-overweight-female groups are 138.80, 164.10, 82.57, 98.74, 36.84, 42.84, 19.48 and 24.33 g per day. This results are higher than those amount of avoidable household food waste in China in the literature by Song et al.(2015), which reported that the average person wasted 43.83 g of food at home per day. The daily excessive food intake is dominated by the grain intake. For example, for both overweight and obese group, on average 31% of daily excessive food intake comes from wheat, and 46% - from rice. Excessive food intake on average accounts for 10.83% of daily food intake for obese people, while making up 2.67% for overweight people. These data are compared with the related studies in Italy and Sweden, which reported that excessive food intake at the population level of 1.533 Mt and 0.71 Mt per year, respectively, and at the individual level of an average of 473.96 and 152.11 g per day, respectively (Franco et al., 2022; Sundin et al., 2021).

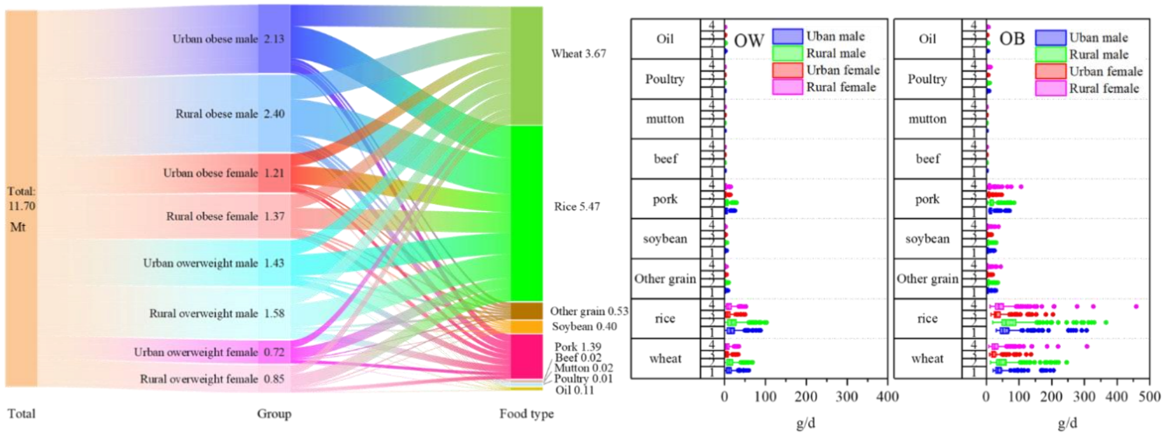

Fig. 2 The excessive food intake in obesity and overweight groups in China. The picture on the left shows the national annual consumption of additional food and its structure, while the picture on the right shows the daily consumption of additional food and its structure for different population groups

3.4 Excessive environmental burden

The environmental impacts associated with excessive food intake in China are calculated by energy footprint (EF), carbon footprint (CF), water footprint (WF) and Ecological footprint (EcoF), distinguishing between eight demographic groups, and splitting the environmental impacts among the "farm to plate" stage of each foodstuff. Excessive food intake causes a considerable environmental impact. Fig. 3 shows the environmental footprints caused by excessive food intake. For example, the CF of excessive food intake in China is estimated at 37.53 Mt CO_2 eq/year, accounting for approximately 3.43% of the total food production in China (Lin et al., 2015), which corresponds to an environmental burden of about 59.85% and 40.15% for obese and overweight people, respectively. The corresponding value for Italy and Sweden is 6.15 Mt of CO_2 eq and 1.2 Mt CO_2 eq per year (Franco et al., 2022; Sundin et al., 2021). Specifically, the average CF caused by excessive food intake of urban-obese-male, rural-obese-male, urban-obese-female, rural-obese-female, urban-overweight-male, rural-overweight-female, urban-overweight-female and rural-overweight-female groups are 159.95, 189,11, 95.15, 113,78, 44,15, 51,34, 23.34 and 29.02 kg CO_2 eq annually. With exception of overweight females, the carbon footprint of excessive food intake has already surpassed that of the average person's carbon footprint resulting from food waste at home (Song et al., 2015). In addition, the EF, WF and EcoF caused by excessive food intake in China are estimated at 10.72 Mtce, 300.82×10^9 m^3, and 522.99×10^9 m^2, respectively.

With respect to the contribution of different population groups to the environmental burden due to excessive food intake, it is interesting to highlight that rural-obese-male is the group with the largest impact in all four environmental footprints, while urban-overweight-female group has the least impact. Specifically, rural-obese-male group contributes 20.18% of the CF of China's excessive food intake, compared to 6.30% for the urban-overweight-female group. It is worth noting that overall the obese male group is responsible for almost 40% of all environmental footprints. Meanwhile, the contribution of overweight males was even higher than that of obese females, which is most likely due to the high number of obese and overweight men in China.

Overall, cereal-based products were the largest contributors to the EF, CF and WF of excessive food intake in China. However, meat-based products contributed most to the EcoF. In cereal-based products, rice provided the largest contribution to the WF, CF and EcoF, with a range from 10.71%~35.10%, while wheat was more responsible for the EF, with a value of 30.48%. In meat-based products, pork makes the greatest contribution to all environmental footprints, with a range from 31.09%~41.13%. In addition, as for each food type, pork is also the largest contributor to all environmental impacts.

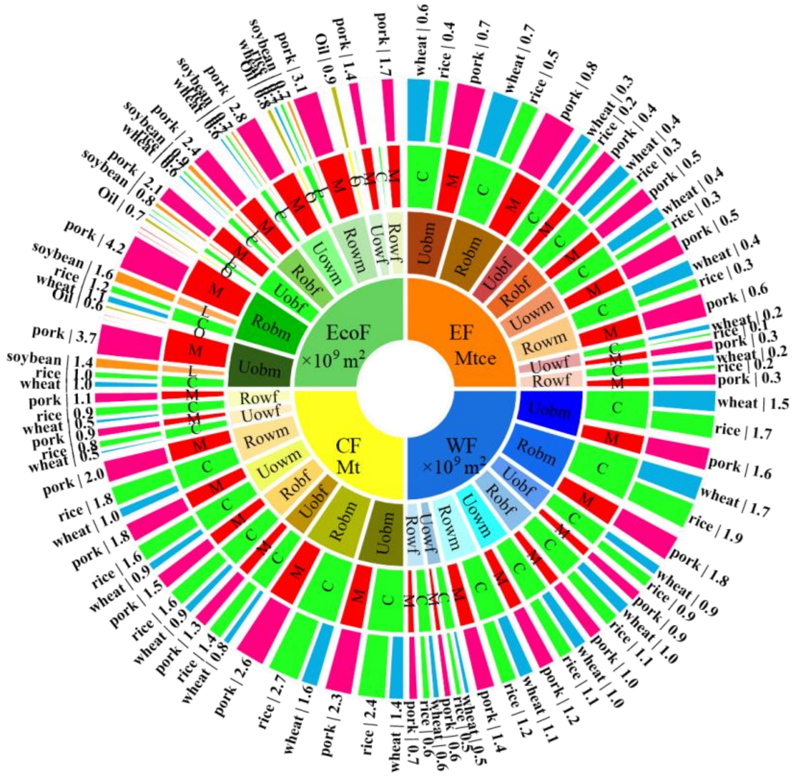

Fig. 3 The environmental impact of excessive food intake. Note: Uobm indicates urban-obese-male group, similarly, Robm represents rural-obese-male group, Uobf means urban-obese-female group, Robf means rural-obese-female group, Uowm means urban-overweight-male group, Rowm rural-overweight-male, Uowf means urban-overweight-female and Rowf means rural-overweight-female groups; C represents cereal group, M indicates meat group, L means legume group and O means oil group.

4. Discussion

Excessive food intake is at the same time a reason for and a consequence of the obesity and overweight epidemic. This study found that excessive food intake and its corresponding environmental impact in China is considerable. It has exceeded the amount and impact of avoidable household food wastes. The quantity of food corresponding to excessive food intake reaches 11.70 Mt annually, for a total EF, WF, CF and EcoF of 10.72 Mtce, 300.82×10^9 m^3, 37.53 Mt CO_2 eq and 522.99×10^9 m^2 every year, respectively. Results also highlight the dominant role of cereals and meats intake. More than 90% of excessive food consumption is derived from cereals, and 70-90% of the corresponding environmental impact is from these two food groups. China is a country that feeds mainly on rice and wheat, with a classic diet consisting of cereals, vegetables and a few meats (Du et al., 2002; Talhelm and Oishi, 2018). Prior to 1993, faced with a severe food shortage, China had a food rationing system to guarantee a safe food supply. During this period, meat was a scarce resource and therefore grains were consumed in large quantities as a cheaper food to support the body's daily activities (Gao et al., 1996). With the transformed economy and reformed food policies, China's rationing system has been gradually abolished, which has greatly increased the availability of diversified foods in urban areas over the past 30 years (Xiong et al., 2020). China has transformed very rapidly from the pattern of the past receding famine stage to that of diet-related diseases, caused by compensatory consumption of food, especially animal-based food (Du et al., 2002). China's economy is projected to continue to grow in the future, and as the disposable income per capita rises, as well as the food supply system improves, this country will face even more serious challenges of excessive food intake and its environmental impacts. In fact, per capita refined cereal consumption has been declining, while per capita meat consumption has been surging (Liu et al., 2021). Although dairy consumption is now well below the recommended values, it will continue to grow in China in the future as nutritional knowledge spreads and Western dietary patterns are popularized. Based on these, the share of animal-based food will increase, which could potentially result in even bigger environmental impacts in the future.

The total excessive food intake and its environmental impacts are large in China; however, the per capita average is much lower than in some high-income European countries. Compared with Italy and Sweden, China's total excessive food intake is 7.64 and 16.47 times higher than those of these two countries respectively, resulting in a corresponding carbon footprint that is 6.10 and 31.27 times higher than those of the two countries. On an individual level, however, China's per capita excess food intake (averaged across all eight groups) is only 11.49% and 31.24% of theirs, and its per capita carbon footprint is a mere 25.30% and 21.80% of theirs. respectively (Franco et al., 2022; Sundin et al., 2021). Therefore, avoiding overeating and reducing the obese/overweight population in China should be noticed more widely at the collective level. When a sufficient number of people join the effort, China will achieve significant benefits in terms of food conservation, reduction in obesity and its health burden, and mitigation of the environmental impact of excessive food intake.

According to our results, excessive food intake exhibited distinct differences across the sub-populations. It is evident that when all else is equal, excessive food intake is significantly higher in males than in females, and higher in rural areas than in urban areas. The prevalence of overweight and obesity was higher in Chinese males (Tian et al., 2014). Although westernization has greatly influenced eating and living habits with the advance of globalization, traditional beliefs about body image persist, which means a larger body type is accepted and still may be culturally associated with a greater socioeconomic status (Kanter and Caballero, 2012). In addition, women had higher awareness, body shame, and actual/ideal weight discrepancy, and lower body esteem than men (McKinley, 1998). With the combination of these drivers, the male group is responsible for more excessive food intake and its environmental impact. Rising rural body-mass index is the main driver of the global obesity epidemic in adults (NCD Risk Factor Collaboration (NCD-RisC), 2019), thus it is not surprising that excessive food consumption is higher in rural areas. Consistent with the overall traditional cultural tenets, in many Chinese rural areas, it was believed that eating is a blessing, and a fatty appearance (overweight and obesity) symbolized prosperity. Being overweight and obese were not considered as risk factors of NCD. In addition, the relatively lower education may be a predictor for higher prevalence of overweight and obesity among the rural population.

Most past studies have emphasized the importance and necessity of solutions from the consumption-side for addressing the environmental issues originating from household food waste (Lin and Guan, 2021; Liu, 2014). Yet excessive food intake is even more of a factor to consider, not only in relation to its negative impact on health, but also in relation to changes in the environmental protection. As mentioned in some studies, excessive food intake is essentially a metabolic waste and is a significant component of food waste (Franco et al., 2022). Meanwhile, as our research shows, the food consumption and environmental impact of excessive food intake have exceeded even the avoidable household food waste. Therefore, particularly for developing countries such as China, efforts aimed at behavioral changes appear to have greater potential to reduce unnecessary food demand and alleviate adverse environmental impacts. The results of this study demonstrated the crucial importance of reducing the overall excessive food intake, no matter its composition and quality. However, from an environmental perspective, reducing the excessive consumption of meat and refined grains would be the most effective. It is certain that this recommendation should be accompanied by improvements in dietary quality. Thus combining both nutritional quality and environmental impact of food choices is fundamental when considering excess food intake. Given the differences in excessive food intake among populations with different demographic and regional characteristics, much more attention should be paid to the underlying differences in dietary, habitual and lifestyle within population and associated emissions. Moreover, great efforts should be made to raise public awareness of the dual impact of excessive food intake on health and environmental sustainability. Promoting education and awareness campaigns that advocate for avoiding excessive food intake and shifting towards environmentally and healthily friendly dietary patterns will make a substantial difference in improving national health, reducing unnecessary food consumption and mitigating diet-related environmental burdens in China.

The present study estimated excessive food consumption among adults aged 18-75 years in China, and did not consider children and adolescents and people over 75 years of age. Therefore, the reality of excessive food consumption should be greater than the values reported in this study, and the corresponding environmental impacts are more severe. In addition, this study compared the daily intake of each food group of Chinese residents with the recommended dietary guidelines to define the food groups that are responsible for excessive food consumption. However, the dietary guidelines are based on population-based considerations and lack careful consideration of individuals, which is one of the reasons for the discrepancy between the study results and the reality. For some people, their bodies may require a higher than normal intake of protein (above the dietary guideline recommendations for the wider population), so excess meat and egg intake should not be excessive for that group of people. It is important to take into consideration both the heterogeneity of the underlying data and the high variability, which is intrinsic in the LCA methodology (i.e. CF and EF estimates can be highly variable depending on geography, seasonality, method of production, the energy source for processing, etc.), when analyzing the results from this study. The results should therefore be interpreted as an estimate of the magnitude of the climate impact associated with excess food intake, rather than exact. In comparison to similar studies that assign excessive energy intake to all foods included in the daily diet, our study account only for the excessive food intake above the daily nutritional requirements. As a result, it calculates the environmental impact in a more detailed way with due regard to the nutritional requirements.

Certainly, some limitations inevitably exist in this research. Environmental footprints were calculated based on the processing of local food production and consumption, without considering differences in environmental impacts resulting from food imports and exports in global trade. Some results also need to be read with caution when used to explore the demographic characteristics of excessive food intake and the corresponding causes, given that this is a exploration with a static model only involving some of the potentially important influencing factors. In addition, this study adopted a widely used method, BMI, to definite obesity and overweight, but whether this method is a true indicator of obesity is still under debate in the scientific community. For example, there are other measures of obesity such as waist circumference. As mentioned above, currently per capita excessive food intake in China is small. In the foreseeable future, this number will likely increase, but the scale of it and the environmental impact depend on many factors. In order to estimate them a more sophisticated dynamic model should be conducted to reveal more comprehensively elaborate on the processes, demographic characteristics and key influences of excessive food intake and its environmental impacts in China.

5. Conclusion

Excessive food intake closely affects human and environmental health, and has a direct and indirect influence on the achievement of the Sustainable Development Goals. However, excess food intake is currently not addressed in plans for higher environmental sustainability, such as ensuring food security, reducing inequalities and mitigating environmental impact. As obesity levels rise globally, more and more people continue to consume more food than the recommended caloric intake, which may cause the amount of excessive food intake to climb globally. This study provides the first assessment of the extent of excessive food intake in China, showing that excessive food intake has surpassed the amount of avoidable household food waste. It significantly contributes to the overall environmental impact of the food supply chain, and causes environmental impacts. In addition, we find significant differences in excessive food intake among sub-populations with different demographic characteristics and urbanization levels. .

Findings from this study have meaningful policy implications. It is unquestionable that reducing all excessive intake, especially of refined cereal and meat has a considerable impact on the reduction of the environmental impacts. Demographic differences in urbanization level and gender are worth more attention, as they are important for understanding the causes of excessive food intake and formulating targeted dietary adjustment strategies. Meanwhile, excessive food intake deserves the same consideration as other dietary issues. It requires a deeper understanding of social, environmental, and economic implications of excessive food intake at both individual and collective levels. This study provides a fundamental methodological framework applicable for future research in this field, and further aids both policy makers and consumers to have a better understanding of the impacts of excessive food intake.

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