Incorporating carbon emissions from landfills and wastewater treatment into a household emission inventory for systematically analysing household behaviour

Junsong Jia, Zhihai Gong, Chundi Chen, Zhongyu Gu and Dongming Xie

ABSTRACT

In this paper, taking Nanchang, China, as an example, we first systematically divided household behaviour into three components: entrance (eight lifestyles), kernel (energy uses and private vehicles) and outlet, which was a concern of few scholars and contained the carbon emissions (CEs) of domestic wastewater treatment and landfills. The CEs of entrance were calculated by consumer lifestyle approach and others by Intergovernmental Panel on Climate Change (IPCC). The results showed all the CEs of entrance, kernel and outlet had increasing trend from 1998 to 2014. They were 172.65×10^4, 22.19×10^4 and 9.18×10^4 t CO_2 in 1998 and increased to 283.10×10^4, 78.83×10^4 and 23.03×10^4 t CO_2 in 2006 and to 458.43×10^4, 206.82×10^4 and 33.55×10^4 t CO_2 in 2014. Their shares were 66%–85%, 11%–30% and 4–6%, respectively. Although the CE shares of wastewater treatment and landfills are currently modest, they will become increasingly greater in the future. Thus, it is significant to construct this new accounting frame, especially for analysing sustainable household consumption behaviour. Finally, some attributes of the new frame are clarified, and related policy implications are put forward.

Key words | carbon emissions (CEs), consumer lifestyle approach (CLA), consumption behavior, household emission inventory, systematic perspective, wastewater treatment

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INTRODUCTION

It has been reported by the Intergovernmental Panel on Climate Change (IPCC 2013) that human activities likely (more than a 95% possibility) have caused most (more than 50%) of the global average surface temperature rise since the 1950s (Qu *et al.* 2016). As one domain of human activities, households have consumed plenty of direct or indirect energy and increased carbon emissions (CEs), which has attracted more and more attention all over the world (Motsholapheko *et al.* 2012; Berhanu & Beyene 2015; Abbas *et al.* 2016; Li *et al.* 2016; Miehe *et al.* 2016; Wang *et al.* 2016). For instance, Liu (2010) found that the indirect energy consumption of households in 2005 had reached 6.3 times that consumed in 1992, and related CEs had increased 5.8 times. Additionally, Feng *et al.* (2011) concluded that approximately 45–55% of total energy use had arisen from households' consumer activities. In addition, Liu *et al.* (2013b) considered that it is better to measure energy consumption or CEs from the consumption side, versus the production side, to design a regional low-carbon road map. Furthermore, households are one of the typical terminals of energy consumption; thus, they should be given priority. In addition, in the United States alone, households had only 4.3% of the total global population, but they were directly or indirectly responsible for approximately

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20% of annual global greenhouse gas emissions (Jones & Kammen 2014). In the UK, Allinson *et al.* (2016) found that CE from households was also high by using an estimation method and a sample of 575 households. In China, there has been rapid economic growth since the reforms of the late 1970s, which has brought about a dramatic improvement in living standards. With this, household consumption has also been gradually rising (Wang & Liu 2015; Wang *et al.* 2015a; Zhang & Xie 2015). It doubled from 157.99 million tce (tonnes of coal equivalent) in 1990 to 396.66 million tce in 2012 (Wang *et al.* 2015b). It was estimated that the household sector had consumed a large amount of goods and services, accounting for more than 70% of the final consumption expenditures in China (Qu *et al.* 2011, 2013, 2015; Xu *et al.* 2015). Liu *et al.* (2011) found that CO_2 emissions from household consumption accounted for more than 40% of total CEs in China from 1992 to 2007. Thus, there is much potential for carbon mitigation in the household consumption field in China.

Theoretically, scientists have put forward some accounting methods or frames for calculating household CEs from their respective districts (Weber & Matthews 2008; Druckman & Jackson 2009, 2010; Hawkins & Dente 2010; Larsen & Hertwich 2011). We can classify these methods into four major types (Dias & Arroja 2012; Zhang *et al.* 2015): emission coefficient methods (ECMs), life cycle assessments (LCAs), input–output models (IOMs) and consumer lifestyle approaches (CLAs). Based on the methods recommended by the IPCC (2006, 2007), ECM calculates CO_2 emissions of direct household energy use by adding up consumption amounts and multiplying them by the CE coefficient. If CO_2 is emitted through means other than direct energy use, we can adjust the related coefficients according to the IPCC reference. However, it is difficult to estimate precisely these coefficients because of different technologies and production conditions; thus, the results are uncertain (Kadian *et al.* 2007; Liu *et al.* 2012, 2013a). Fan *et al.* (2013) commented that changes in CE coefficients had an inconspicuous and yet overall negative effect upon CE estimation, which should be duly noted. LCA provides an integral picture of GHG emissions caused by consumer expenditures (Hertwich 2005; Saner *et al.* 2013). Thus, based on this, we can calculate the related household CE. For example, Alfredsson (2004) adopts LCA to assess the household consumption and corresponding CE of Swedish household activities. Taking the American Virgin Islands as a case, Shirley *et al.* (2012) still adopt this LCA to analyse the CEs of some major goods and consumptions during their extraction, processing, transport, disposal and use stages. However, this method requires abundant data to perform the CE calculation, and it is time-intensive to obtain the data. Thus, it is not feasible to adopt it when some original data are lacking.

IOM is a method of calculating household CE by directly using the input–output tables from the statistical data. This method can show regular data updates in a fixed matrix format. When estimating the household consumption and the related CEs of the Netherlands, Kok *et al.* (2006) divided the input–output analysis into three types. The three types are an input–output analysis directly based on national accounts (IOM-N), an input–output analysis of household expenditure data (IOM-E) and a hybrid analysis combining an input–output model with the process of production and consumption (IOM-P). The obtained results from the three IOMs are very close, with less than 4% deviation. This method is increasingly accepted and applied (Bin & Dowlatabadi 2005; Golley & Meng 2012). In China, related data from the Energy Yearbook and Household Expenditure Table published by the National Bureau of Statistics are directly available. Thus, this method is also extensively used (Peters *et al.* 2007; Minx *et al.* 2011; Zhu *et al.* 2012). However, this method uses a constant technology coefficient, which does not accord with the reality and cannot reflect technological updates (Liu *et al.* 2009). CLA was first used to calculate consumer-oriented energy consumption and related CEs in the United States in 2005. It is often considered the integrated application of ECM and IOM. ECM is adopted to calculate the direct household CEs, while IOM is adopted to estimate the indirect household CEs. However, this method cannot be used directly in China because there is a lack of related original data tables (Dai *et al.* 2012; Fan *et al.* 2012). Thus, Wei *et al.* (2007) made a matching revision based on the reality of the statistical data in China. Thereafter, this updated CLA has been more widely applied (Zhang *et al.* 2013; Wang & Yang 2014). However, the new version still has some obvious shortcomings. For example, it ignores household CEs from landfills or domestic wastewater treatment

(Liang *et al.* 2013; Qin & Han 2013). Thus, we incorporate the CE of wastewater treatment, etc., into the CE inventory of household consumption for systematically assessing household behaviour.

On the other hand, researchers often took all of China or some prominent districts (e.g., Beijing or Shanghai) as a case to study the CE of household consumption. The underdeveloped or developing districts in western or central China remain rarely investigated. Thus, taking a typical underdeveloped city, Nanchang, China, as an example, we first regarded household consumption behaviour as a system with an entrance, kernel and outlet. Then, we incorporated the CEs of wastewater treatment, etc., into the outlets section of emission inventory and completed the whole calculation and analysis based on the CLA method and the IPCC recommendation. Below, the detailed methodology and the innovation of this article are presented. The section after that completes the computation, analysis and discussion of the results. The final section concludes and proposes some reasonable countermeasures for the sustainability of regional household consumption behaviour.

METHODOLOGY

New accounting frame of household consumption's system

In the past, people often ignored the indirect CE from landfills and domestic wastewater treatment when accounting for the CEs of household consumption. For example, Bin & Dowlatabadi (2005) assessed the household CEs of the USA, and Wei *et al.* (2007) calculated the household CEs of China. Both of these works ignored the CEs of landfills and wastewater treatment. Therefore, it is innovative to integrate all these sources' CEs into a whole frame for the CE calculation of household consumption systems in this paper. In other words, it is a new accounting frame of household consumption behaviour to incorporate the CEs of landfills and wastewater treatment as the outlet of a household consumption system. In this new accounting frame, the calculation methods of the kernel and outlet CEs were designed according to the IPCC recommendation. Meanwhile, the CEs of the entrance were calculated using the classic CLA method (Wei *et al.* 2007; Feng *et al.* 2011).

Figure 1 shows the new accounting frame of household consumption behaviour from a systematic perspective and the relative CE scope in this paper. As shown, household consumption is regarded as an integrated system that contains direct and indirect sources. The direct sources are energy (fuels) combustion from the home and personal travel activities of people using cars, motorcycles, and so on. The indirect sources include two parts as well. The first is from the consumption of goods in family life (left and top in Figure 1), which indicates the different lifestyles of diverse people and is the entrance of the household consumption system. Lifestyles may be clothing, food consumption, entertainment, education activities, and so on. Another source comes indirectly from the landfills and domestic wastewater treatment system (right and top in Figure 1), which is also the

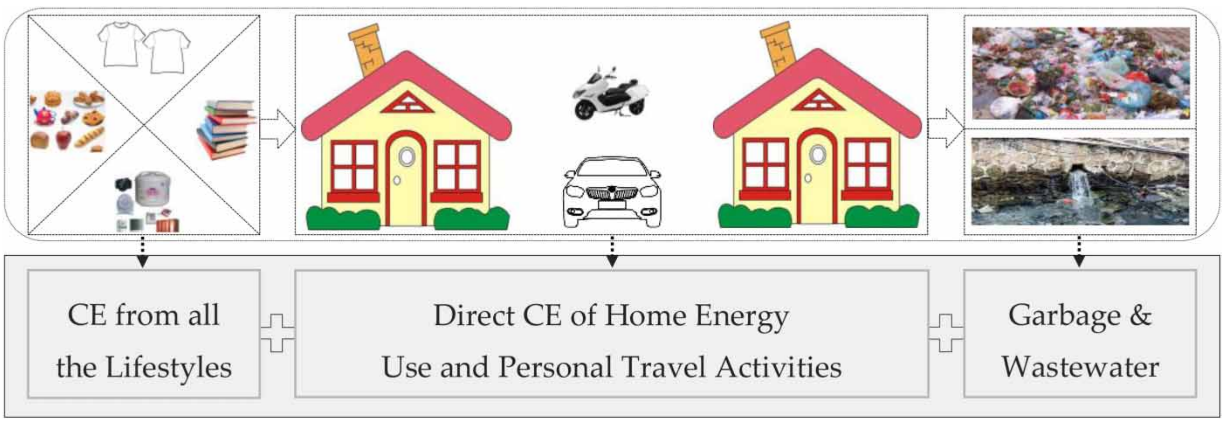

Figure 1 | CE sources and the accounting frame of household consumption behaviour from a systematic perspective.

outlet of the household consumption system. Thus, all the sources can be integrated into a whole accounting frame. We bring them into the rounded rectangle as shown at the top of Figure 1. Similarly, the bottom of the figure indicates the different CEs from these top sources. All of them are indispensable parts of household consumption CEs. Thus, we must calculate all of them, not ignoring any, to sum and obtain total household CEs.

Change in Nanchang's household consumption

Nanchang, the capital city of Jiangxi Province in central China, is at 28° 09′–29° 11′ N and 115° 27′–116° 35′ E, with an administrative area of 7,402 km^2. With socioeconomic development and the deepening of reform and opening to other cultural influences, people's living standards have improved rapidly in Nanchang. Thus, people own more and more cars or motorcycles, and CEs from travel have increasingly grown. Meanwhile, people use more and more electrical household appliances and buy more and more clothing because they have become wealthier and wealthier. Thus, the household energy CEs or matching CEs from clothing and other lifestyle changes have also had the same increasing trend. Briefly, household CEs and all their sub-sections have become greater and greater over the past 30 years. In addition, in the future, the CE share from household consumption may become more and more important. Thus, it is time to more accurately calculate household CEs in Nanchang. Reviewing published articles, there are, up to now, very few studies concerned with this city. Therefore, the work presented in this paper is urgent and necessary.

Specific computations and data source explanations

As previously discussed and shown in Figure 1, household consumption includes three parts: entrance, kernel and outlet. Thus, the relative CEs can also be sorted into three parts from a systematic perspective.

CEs from the systematic entrance of household consumption

The CEs of the household consumption's entrance are the indirect CEs from all the different types of lifestyles. These related lifestyles can be divided into eight classes (Bin & Dowlatabadi 2005; Wei *et al.* 2007; Feng *et al.* 2011) as follows: food, clothing, residence, household facilities and articles, medicine and medical services, transport and communication, culture and education, and miscellaneous commodities. Table 1 shows details of the matching industries. We can calculate their CEs and energy consumption based on the following equation (Wei *et al.* 2007):

$$C_{ind}^{\mathrm{I}} = \sum_{a=1}^{8} (CI_a \times M_a) \times N \tag{1}$$

$$E_{ind}^{\mathrm{I}} = \sum_{a=1}^{8} (EI_a \times M_a) \times N \tag{2}$$

where C_{ind}^{I} is the total indirect CEs from all the different types of lifestyles, its unit is ton-CO_2 (t-CO_2) and E_{ind}^{I} is

Table 1 | The eight different lifestyles and matching industries in Nanchang's Statistical Yearbooks

No.	Consumer expenditure	Related sectors
1	Food	Food processing, food and beverage production
2	Clothing	Textile industry, garments and other fibre products, leather, furs, down and related products
3	Residence	Production and supply of electric power, steam and hot water, gas, and tap water, construction, non-metal mineral and metal products
4	Household facilities and articles	Timber processing, bamboo, cane, palm fibre and straw products, furniture manufacturing and electronic equipment and machinery
5	Medicine and medical services	Medical and pharmaceutical products
6	Transport and communication	Electronic, telecommunications and transportation equipment
7	Culture and education	Papermaking and paper products, printing and record medium reproduction, and cultural education and sports articles
8	Miscellaneous commodities	Tobacco processing, and wholesale, retail trade and catering

Notes: The categories are according to Feng *et al.* (2011), Wei *et al.* (2007) and Bin & Dowlatabadi (2005).

the corresponding energy consumption (tce); a is the class of the lifestyle, $a = 1, 2, \ldots, 8$; CI_a is the carbon intensity of the lifestyle of class a ($CI_a = C_a/G_a$, C_a is the sum of CO_2 emission of industries in class a, while G_a is the sum of the value added of the industries in class a); similarly, EI_a is the energy consumption intensity of the a class lifestyle ($EI_a = E_a/G_a$, E_a is the sum of energy consumption of the industries in class a); M_a is the per-capita expenditure of consumption a; and N is the number of residents, which can be divided into urban (N_{urban}) and rural (N_{rural}). M_a and N can be obtained directly from Statistical Yearbooks. Based on the method of Wei *et al.* (2007), CI_a and EI_a can be calculated as shown in Table 2. Only the three years of data and results from 1998, 2006 and 2014 are illustrated for a more concise and convenient discussion.

From Table 2, we can easily see that most of the CI_d and EI_d had a decreasing trend. This was because the total energy intensity from all the different types of industries also had an overall declining trend as shown in Figure A1. In 1998, the total energy intensity was 0.44 tce/10^4 Yuan. It decreased to 0.34 tce/10^4 Yuan in 2014. From 1998 to 2014, it oscillated up and down, especially in 2006, when it rose to 0.51 tce/10^4 Yuan. Similarly, the CI_d (EI_d) of the third and seventh lifestyles also rose from 1998 to 2006 (Table 2). Analysing further, we found that local government had launched many real estate construction projects (including new campus construction at the university) during the tenth National Five-Year Plan (2001–2006). With the advance of these construction projects, many energy-intensive industries had also been launched. However, at the same time, people had sufficient consciousness and technology to save energy or to improve energy efficiency. Thus, the total energy intensity had a whole growth (not decline) trend from 2001 to 2006. However, people gradually paid much more attention to saving energy and improving efficiency from 2007 to 2014. Therefore, energy intensity started to obviously decrease in 2008 and 2009. In 2009, the energy intensity reached its lowest value. The reason could be the global financial crisis in 2008. We can easily see that total energy consumption obviously decreased, but economic development (GDP) did not stagnate as shown in Figure A1. In the end, why did total energy intensity see an overall decrease? This change was the result of the GDP increasing more than three times from 0.70×10^{11} Yuan in 1998 to 3.01×10^{11} Yuan in 2014. However, during the same time period, total energy consumption increased only 2.37 times (<3) from 3.07 in 1998 to 10.35 million tce in 2014 (Figure A1).

Table 2 | Calculated CI_d and EI_d in 1998, 2006 and 2014

	CI_d (t CO_2/10^4 Yuan)			EI_d (tce/10^4 Yuan)		
No.	**1998**	**2006**	**2014**	**1998**	**2006**	**2014**
1	0.430	0.314	0.150	0.627	0.458	0.126
2	1.127	0.271	0.149	1.614	0.416	0.096
3	2.690	2.752	1.665	3.623	3.812	1.692
4	0.279	0.123	0.145	0.428	0.192	0.092
5	0.973	0.231	0.155	1.390	0.335	0.134
6	0.215	0.195	0.172	0.327	0.310	0.121
7	1.580	2.110	0.757	2.183	3.021	0.743
8	0.145	0.035	0.019	0.219	0.055	0.018

Notes: For a comparison objective, we carry out the calculations (containing the following text) on the basis of a constant price in 2010 (the numbers 1–8 refer to the eight consumer expenditures in Table 1).

CEs from the systematic kernel of household consumption

The CEs of the household consumption kernel contain direct CEs from home energy uses and personal travel activities. Home energy uses refer to directly combusted fuels. Their CEs can be calculated using the following equation (IPCC 2006, 2007, 2013):

$$C_{dir}^{e} = \sum_{i=1}^{n} (E_i \cdot f_i) \tag{3}$$

where C_{dir}^{e} is the direct CEs of home energy use (t-CO_2); i is the category of energy, $i = 1, 2, \ldots, n$; E_i is the use amount of the category i energy, for which related data can be obtained directly from the Statistical Yearbooks of Nanchang published yearly by the local government; and f_i is the CE factor of the different types of energy, which can be calculated using the IPCC guidelines as listed in Table 3. We adopted the 100% value of carbon oxidation at the IPCC's recommendation. The CE factor of heat can be calculated as 0.11 ton-CO_2/GJ based on the equivalent of net calorific value. For Nanchang, we cannot directly obtain the CE factor for electricity. Thus we used the average CE factor

Table 3 | CE factors of different categories of energy

Energy category	Carbon content ($kg\text{-}CO_2/GJ$)[a]	Net calorific value (TJ/Gg)[a]	Emission factor ($t\text{-}CO_2/t$)
Crude coal	25.8	20.9	1.977
Washed coal	25.8	26.3	2.488
Other washed coal	25.8	8.4	0.795
Briquette	26.6	17.6	1.717
Coke	29.2	28.2	3.019
Coke oven gas	12.1	1.6726[b]	7.421[c]
Natural gas	15.3	3.8931[b]	21.840[c]
Crude oil	20.0	42.3	3.102
Gasoline	20.2	43	3.185
Kerosene	19.5	44.1	3.153
Diesel	20.2	43	3.185
Fuel oil	21.1	40.4	3.126
Other petroleum products	20.0	40.2	2.948
Liquefied natural gas (LNG)	17.5	44.2	2.836
Liquefied petroleum gas (LPG)	17.2	47.3	2.983

[a]Default value in IPCC, $1GJ = 10^9$ J, $1Gg = 10^9$ g, $1TJ = 10^{12}$ J.
[b]Unit is KJ/m^3.
[c]Unit is $t\ CO_2/10^4\ m^3$.

for China's electricity as the value of the CE factor for Nanchang electricity. The average CE factor for China's electricity can be easily acquired from the International Energy Agency (IEA) statistics 2013 (Table A1).

Personal travel activities refer to the use of a car, subway, bus, etc., to go to work or for entertainment. During these processes, the CEs from directly combusted fuels are termed C^p_{dir} and can be calculated using the following equation:

$$C^p_{dir} = \sum_{j=1}^{m} (A_j \cdot MTT_j \cdot FET_j \cdot f_{g/d}) \times 10^{-6} \tag{4}$$

where j is the type of travel, $j = 1, 2, \ldots, m$; A_j is the amount of travel j; MTT_j is the average annual number of kilometres travelled using the travelling mode j (km/vehicle/year); FET_j is the fuel economy of the travelling mode j (L/km); and $f_{g/d}$ is the CE factor for gasoline or diesel ($g\text{-}CO_2/L$), which are listed in Table 3. The MTT_j and FET_j can be obtained from Wang *et al.*'s (2012) article and A_j can be obtained from the Statistics Yearbook data.

CEs from the systematic outlet of household consumption

The CEs of the household consumption outlet include indirect CEs from landfills and domestic wastewater treatment. Using the IPCC recommended method of the First-Order Decay Model (FODM), we can calculate the indirect CEs of landfills using the following equation:

$$C^g_{ind} = 21 \times \left[\sum_k (CH_{4k,t} - R_t)\right] \cdot (1 - OX_t) \tag{5}$$

where C^g_{ind} is the indirect CE of a landfill ($t\text{-}CO_2$); k is the garbage type; t is the statistical year; $CH_{4k,t}$ is the CH_4 production output of the garbage type k during the inventory year t (ton); R_t is the CH_4 recovery number for the inventory year t (ton); and OX_t is the oxidation ratio for the inventory year t (%). We can obtain the $CH_{4k,t}$ and R_t data of household garbage from the Statistical Yearbooks, bulletins or collections of the local government. The default OX_t values are adopted based on the IPCC suggestion.

Similarly, the indirect CEs of domestic wastewater treatment can be calculated using the following equation:

$$C^w_{ind} = 21 \times \left\{\left[\sum_{b,c} (U_b \cdot T_{b,c} \cdot f_c)\right] \cdot (TOW - S) - R\right\} \tag{6}$$

where C^w_{ind} is the indirect CEs of household wastewater treatment ($t\text{-}CO_2$); b is income group such as low, medium and high; c is the system of disposing wastewater for the inventory year; U_b is the population percentage of the group b; $T_{b,c}$ is the degree of the system c used by the group b; f_c is the CE factor of the system c; TOW is the total amount of biodegradable organic matter from the household wastewater (ton); similarly, S is the total organic matter discharged by the sludge for the inventory year (ton); and R is the total methane amount recovered during the inventory year (ton). The U_b and TOW data can be obtained from the Statistical Yearbooks, bulletins, and so on. For the data of $T_{b,c}$, f_c, S and R, we can use their default values on the basis of IPCC's suggestion.

Let C_H denote the total CE of sustainable household consumption and C_{dir}, C_{ind}, C_{ent}, C_{ker} and C_{out} denote the total direct CE, indirect CE, entrance CE, kernel CE and outlet CE, respectively. All their units are in t-CO_2. Based on the new methodology proposed in this article, we have the following:

$$C_{ker} = C^{e}_{dir} + C^{p}_{dir},\ C_{ent} = C^{l}_{ind},\ C_{out} = C^{g}_{ind} + C^{w}_{ind} \tag{7}$$

$$C_{dir} = C_{ker},\ C_{ind} = C_{ent} + C_{out} \tag{8}$$

$$\begin{aligned} C_H &= C_{dir} + C_{ind} = C_{ker} + C_{ent} + C_{out} \\ &= C^{e}_{dir} + C^{p}_{dir} + C^{l}_{ind} + C^{g}_{ind} + C^{w}_{ind} \end{aligned} \tag{9}$$

RESULTS AND DISCUSSION

Different sources of CEs

Indirect CEs of different lifestyles from the entrance

Figure 2 shows the indirect CEs of different urban (rural) lifestyles and their respective shares in 1998, 2006 and 2014 in Nanchang. As shown, the third expenditure item (residence) was the largest of all the eight items. In 1998, residential CE in the urban areas of Nanchang was 57.07×10^4 t CO_2, and its share of all the eight CEs was 38%. In 2006, this CE rose gradually up to 87.11×10^4 t CO_2, and its share was a slight decrease to 34% for all the CEs. However, it rose obviously and rapidly up to 291.48×10^4 t CO_2 and 68% in 2014. In the rural areas of Nanchang, we cannot neglect residential CEs, which is not in accordance with the results of Feng *et al.* (2011) and Wei *et al.* (2007).

Similarly, the residential CEs in the rural area were 9.55×10^4 t CO_2, and their share of all the eight CEs was 40%. These indexes rose gradually to 12.47×10^4 t CO_2 and 49% in 2006 and rose rapidly to 23.08×10^4 t CO_2 and 76% in 2014. The reason could be the large expansion in the real estate industry (REI) and peoples' awareness (attitude) to buy the corresponding property (house). In the early stages of the REI expansion in 1998–2006, the price of property clearly increased more than other ordinary goods. People believed that the price of real estate could decrease to a rational range. Thus, only some of the wealthy people bought houses, and the number was not great.

However, people found that the price of property (houses) always increased and thought it could not decrease any further after many years. In particular, the central government launched an infrastructure investment of $4 trillion to promote economic growth following the stagnation brought about by the global financial crisis in 2008. After this, people thought it was worth buying houses. Thus, all citizens of Nanchang were trying their best to buy a house from 2007 to 2014, which resulted in the residential CE and its share reaching their greatest values in 2014.

The CEs of the seventh item (culture and education) experienced both an increase and decrease. In 1998, in urban areas it was 23.66×10^4 t CO_2, and its share of all the eight CEs was 16%. This grew rapidly to 96.17×10^4 t CO_2 (37%) in 2006 and quickly decreased to 61.77×10^4 t CO_2 (14%) in 2014, respectively. The trend in rural areas is similar to that of urban areas. The reason could be the large expansion in infrastructure of the educational system from 1998 to 2006. However, this expansion decreased from 2007 to 2014; thus, the corresponding CE decreased. Similarly, the urban CEs of the first[t] item (food) had a slight oscillating change. However, the share on the whole decreased because of the growing amount of the other seven items' CEs (Figure 2(b)). However, the indirect CEs of rural food steadily decreased during the study period (Figure 2(c) and 2(d)). The reason could be that more and more young people moved to cities to live and work, and thus, old people or children remained in rural areas. Old people and young children spend less on food than adults. The CEs of the second item (clothing) as a whole showed a decreasing trend, especially in rural areas. The reason could be the scientific and technological improvement in the related manufacturing industry. It should be noted that the CEs of the fourth, fifth, sixth and eighth items have a relatively small share (5–8%), and the indirect energy consumption of all these different lifestyles had a similar change to their CEs (Figure A2 in the Appendix), but they are omitted to save space.

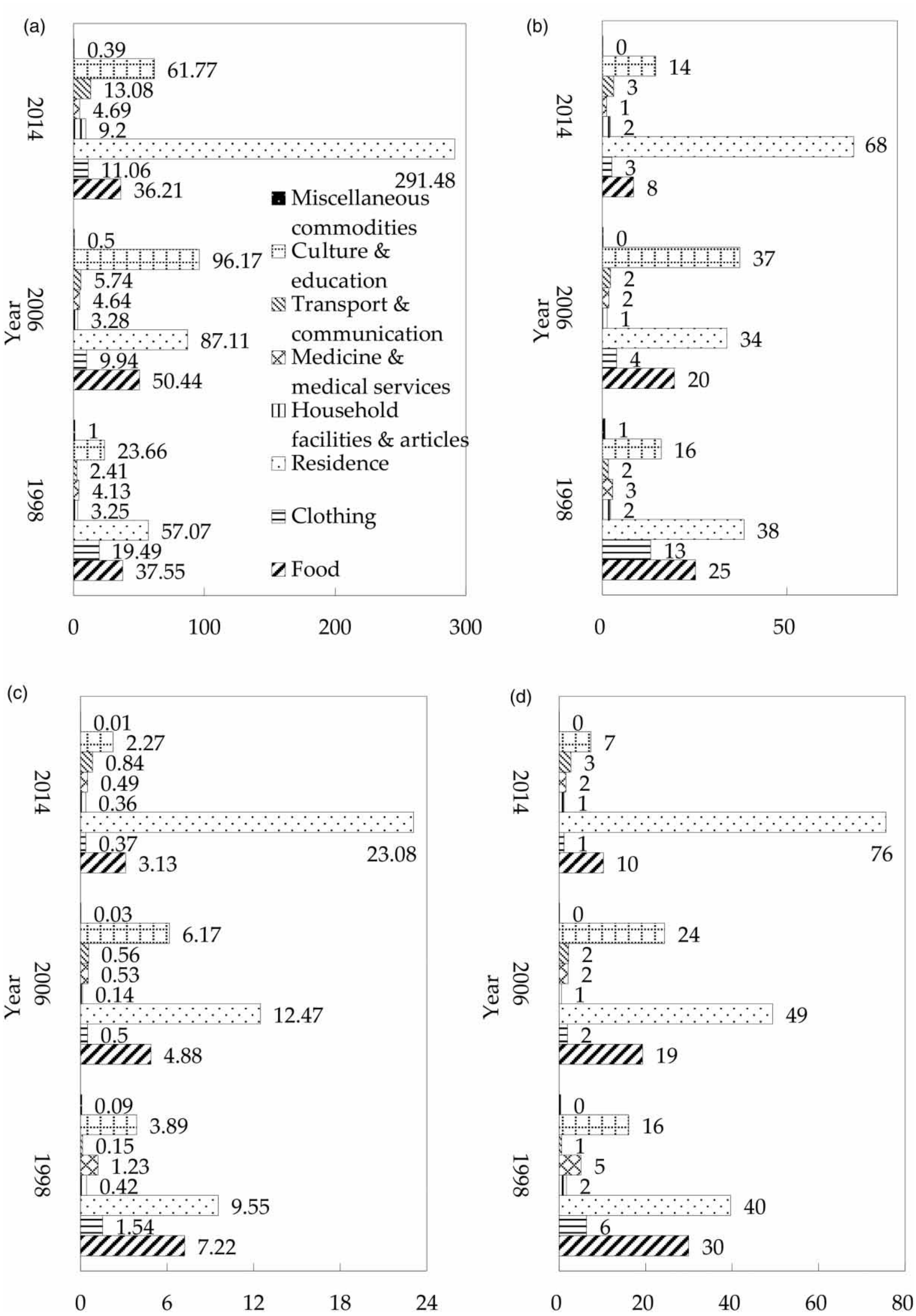

Figure 2 | The indirect CEs of different urban (rural) lifestyles and their respective shares in 1998, 2006 and 2014 in Nanchang. (a) Indirect CE of urban different lifestyles (10^4 t CO_2); (b) Shares of the CE of urban different lifestyles (%); (c) Indirect CE of rural different lifestyles (10^4 t CO_2); (d) Shares of the CE of rural different lifestyles (%).

Direct CEs of home energy use and personal travel activities from the kernel

Figure 3 shows the direct CEs of household energy uses and their respective shares. The major household energy sources of Nanchang are coke oven gas, natural gas, liquefied petroleum gas (LPG) and electricity. People commonly used coke oven gas in 1998. With the improvement in living standards, coke oven gas use gradually increased to a maximum amount of 114.35 million m^3 in 2010 (Figure 3(a)). However, because natural gas is a much safer fuel than coke oven gas for household use, by 2012, people had started to use natural gas instead of coke oven gas as a safer alternative. In 2014, natural gas use increased to 73.71 million m^3 with further socioeconomic development (Figure 3(a)). Direct CEs of coke oven gas were 0.46×10^4 t CO_2 in 1998, increased to 0.67×10^4 t CO_2 in 2006, but declined dramatically to 0 in 2014 (Figure 3(b)). Inversely, direct CEs of natural gas were 0 and 0 in 1998 and 2006, respectively, but increased to 4.39×10^4 t CO_2 in 2014 (Figure 3(b)).

The CEs of LPG increased from 2.55×10^4 t CO_2 in 1998 to 4.26×10^4 t CO_2 in 2006 and to 4.70×10^4 t CO_2 in 2014 (Figure 3(b)). Similarly, the CEs of electricity increased from 15.61×10^4 t CO_2 in 1998 to 40.46×10^4 t CO_2 in 2006 and to 64.61×10^4 t CO_2 in 2014 (Figure 3(b)). The shares of the two CEs (LPG and electricity) were greater than 94% from 1998 to 2014 (Figure 3(c)). However, the share of LPG was 14% in 1998, and it decreased to 10% in 2006

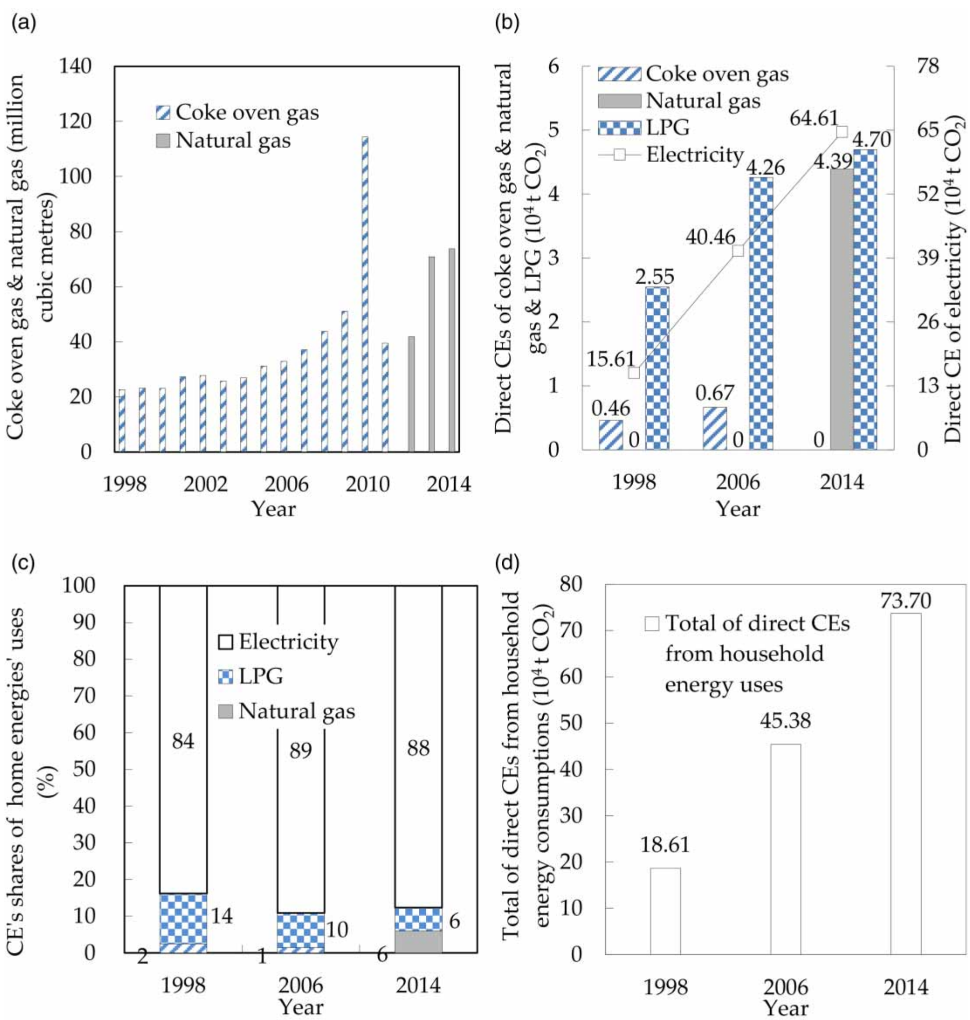

Figure 3 | Direct CEs of household energy consumption and their respective share.

and subsequently decreased to 6% in 2014. This was because the CEs of electricity had a faster growth rate than those of LPG (Figure 3(b)). In the end, no matter the changes in direct energy-related CEs of all types of household items, their total CEs always increased. They increased from 18.61×10^4 t CO_2 in 1998 to 45.38×10^4 t CO_2 in 2006 and steadily increased to 73.70×10^4 t CO_2 by 2014 (Figure 3(d)).

Figure 4 shows the direct CEs of personal travel activities and their respective share. The major vehicles of Nanchang are motorcycles, steering wheel tractors and private cars. It should be noted that travel CEs were differentiated from the transport CEs of the entrance's lifestyles. The travel CEs here were from the direct combustion of family vehicle fuels. Transport CEs of lifestyles were the indirect CEs from peoples' public activities in daily life such as airplane, bus, boat and train travel.

In 1998, CEs from private cars were 2.52×10^4 t CO_2 (Figure 4(a)). This increased rapidly to 30.18×10^4 t CO_2 in 2006 and 130.14×10^4 t CO_2 in 2014. The share of private cars' CEs was 70% in 1998. It increased rapidly to 90% in 2006 and was 98% in 2014. Similarly, CEs from steering wheel tractors were 0.17×10^4 t CO_2 in 1998. This increased to 0.98×10^4 t CO_2 in 2006 and to 2.72×10^4 t CO_2 in 2014, increasing more slowly than the CEs of private cars. Thus, the share of steering wheel tractor CEs decreased from 5% in 1998 to 3% in 2006 and to 2% in 2014 (Figure 4(b)).

The CEs from motorcycles were 0.89×10^4 t CO_2 in 1998. They increased rapidly to 2.29×10^4 t CO_2 in 2006. However, unusually, they decreased rapidly to 0.26×10^4 t CO_2 by 2014. This change was because people gradually abandoned motorcycles in favour of private cars as transportation with the obvious improvement in living standards in recent years. In addition, the share of motorcycle CEs decreased from 25% in 1998 to 7% in 2006. Another reason was that motorcycle CEs increased more slowly than the CEs of private cars. Thus, when considering these two reasons, we can readily understand how the share of motorcycle CEs decreased to nearly 0% in 2014 (Figure 4(b)).

Indirect CEs of landfills and domestic wastewater treatment from the outlet

Figure 5 shows the indirect CEs of landfills (a) and domestic wastewater treatment (b). As shown, with population growth and the improvement in living standards, more and more artificial goods have appeared on the market in Nanchang. People have consumed increasingly more food, clothes, appliances and so on, and thus, household garbage and the CEs of landfills has increased. The indirect CEs of landfills were 2.35×10^4 t CO_2 in 1998, increasing to 15.08×10^4 t CO_2 in 2006 and 25.05×10^4 t CO_2 in 2014 (Figure 5(a)).

Similarly, the CEs of domestic wastewater treatment had a steadily increasing trend. The indirect CEs of domestic

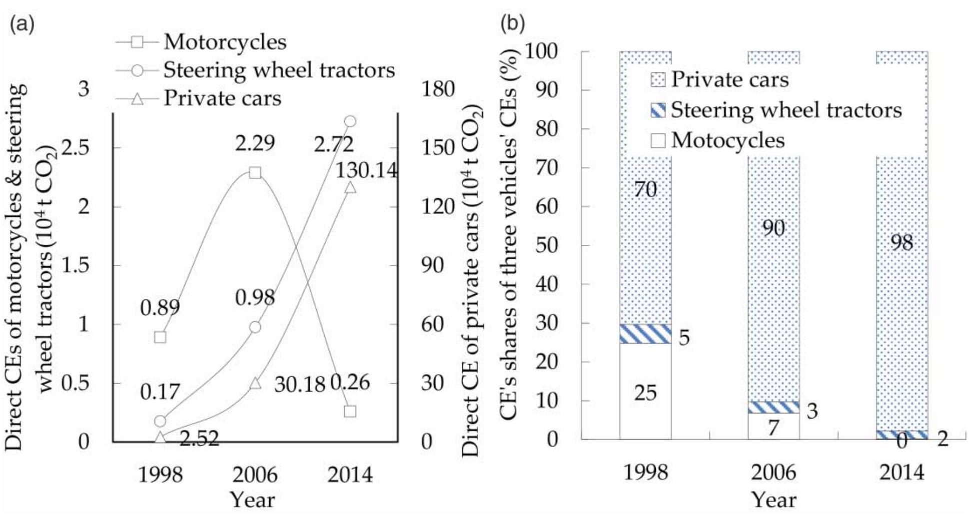

Figure 4 | Direct CEs of personal travel activities and their respective share.

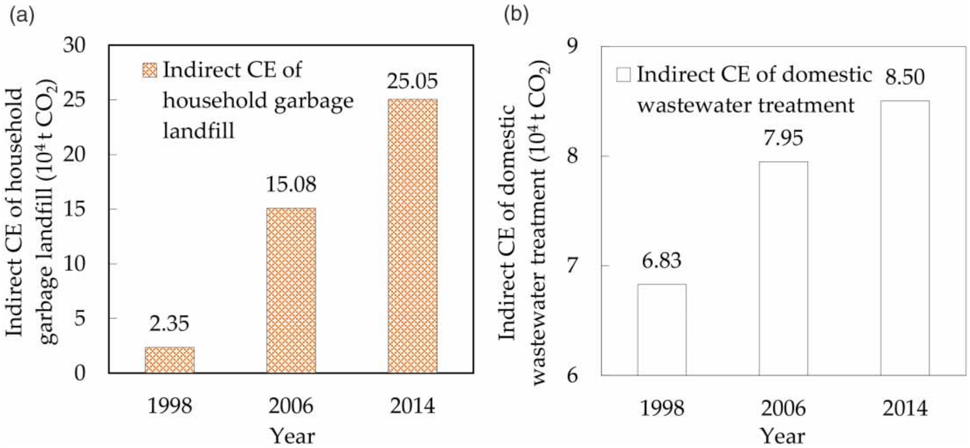

Figure 5 | Indirect CEs of landfills (a) and domestic wastewater treatment (b).

wastewater treatment were 6.83×10^4 t CO_2 in 1998, increasing to 7.95×10^4 t CO_2 in 2006 and 8.50×10^4 t CO_2 in 2014 (Figure 5(b)). This was mainly because more and more people moved to the urban areas of Nanchang with socioeconomic development.

Total CE of the household consumption system

Figure 6 shows the CEs of the entrance, kernel and outlet of the household consumption system and the shares of these CE sources: lifestyle, home energy use, vehicles, and garbage and domestic wastewater. The CEs of the entrance were the total CEs of the different categories of lifestyles. In 1998, they were 172.65×10^4 t CO_2, and they increased to 283.10×10^4 t CO_2 in 2006 and 458.43×10^4 t CO_2 in 2014 (Figure 6(a)). This was a normal and natural phenomenon with the socioeconomic development and the improvement in living standards. However, at the same time, the CEs of the kernel and outlet increased more rapidly than the entrance; thus, the share of the entrance CEs overall had a decreasing trend. The share of entrance CEs was 85% in 1998. It decreased to 74% in 2006 and 66% in 2014. However, all in all, CEs of the household consumption system came mainly from different lifestyles or the entrance (CE share $\geq$66%, Figure 6(b)).

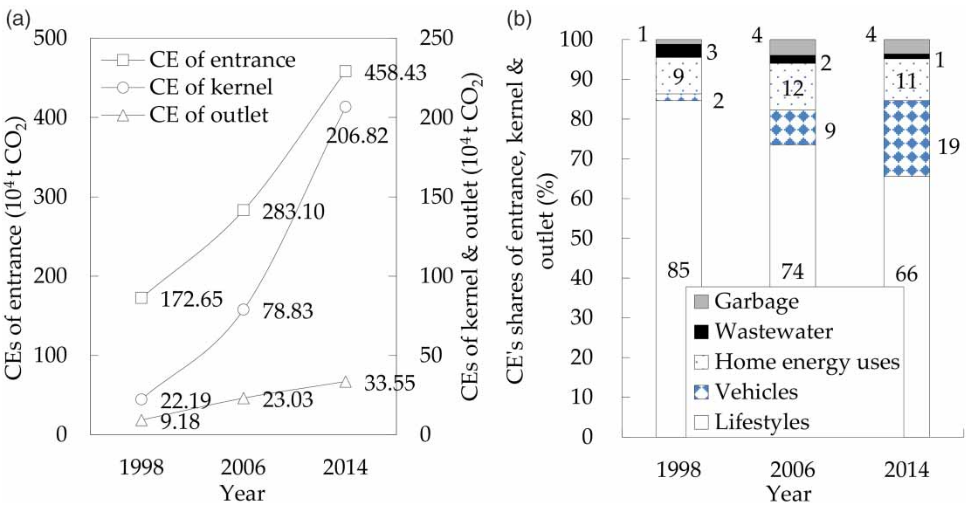

Figure 6 | The CEs of the entrance, kernel and outlet of the household consumption system and the shares of these CE sources (lifestyle, home energy use, vehicles, garbage and domestic wastewater).

The CEs of the kernel were from fuel combustion of the household itself and private vehicles. In 1998, this was 22.19×10^4 t CO_2, but it increased rapidly to 78.83×10^4 t CO_2 in 2006 and 206.82×10^4 t CO_2 in 2014. It had the fastest growth rate. The share of the kernel's CEs was 11% (=9% + 2%) in 1998. It increased to 21% (=12% + 9%) in 2006 and 30% (=11% + 19%) in 2014. Among the kernel, the CEs of private vehicles had the greatest increase. Thus, the CE share of household fuel combustion had a slight decrease. The CEs of the outlet were from landfills and domestic wastewater treatment. In 1998, this was 9.18×10^4 t CO_2. It increased to 23.03×10^4 t CO_2 in 2006 and 33.55×10^4 t CO_2 in 2014. It had the slowest growth rate of the three parts of the household consumption system. In addition, the share of the outlet's CEs was the least of the three stages. In 1998, the share was 4% (=1% + 3%), and it was 6% (=4% + 2%) in 2006 and 5% (=4% + 1%) in 2014.

It should be noted that the CE share of domestic wastewater treatment and landfills was in the range of 4–6% from 1998 to 2014. This share was not very substantial, but it was not negligible. The main reasons were as follows. (1) The absence of some statistical data, which led to a lower estimation of results. For example, we directly used the default value of the total methane number *R* based on the IPCC recommendation, which might not accord with the reality of Nanchang and produce lower computational results. (2) The population-related data were mainly based on the statistics of a household with registration information. This source ignored the large number of migrants who were living in Nanchang but did not register household information. Thus, these data might also make the results calculated smaller than otherwise. (3) The accounting method itself might also lead to some deviations and smaller results. For example, the accounting method of domestic wastewater treatment contained too many parameters, which must be selected according to the actual situation of the specific region. This fact inevitably led to some errors in selection. Nevertheless, as far as the current result was concerned, it could still reflect the fact that the CE from landfills and wastewater disposal systems was not negligible and had a certain importance in the total CEs of the household consumption system. Moreover, with the implementation and promotion of China's low-carbon development strategy, various lifestyles (including direct household energy use and personal travel, etc.) will only evolve in the direction of energy conservation and lower CEs. In other words, in the long run, the CE share generated by the entrance and kernel of the household consumption system will be less and less. In turn, the CE share of the household outlet (wastewater and waste disposal) will become increasingly greater in the future. Therefore, we could conclude that it was very necessary and significant for us to incorporate the CEs of wastewater treatment and waste disposal into a household emission inventory in this paper.

Comparisons to other countries or regions

Total population, per capita CEs and CEs per GDP of the household consumption system from Nanchang and other regions or countries such as India, Brazil and the USA are listed in Table 4 for the convenience of analysis and comparison. From this, we can see whether there is consideration of CEs of the outlet or not. The CEs per capita of household consumption in Nanchang are always equivalent to the lower-middle level of urban China (1.12 < 1.28–1.35 < 1.49 t CO_2). These results show that the whole CE accounting process of Nanchang's household consumption is accurate and reliable. Moreover, the results are consistent with the reality of social and economic development in Nanchang. It is known that the level of economic development in Nanchang is only moderate and slightly lower than many other areas in China. In addition, the results are closer to the values of India (0.9 t CO_2) and Brazil (1.5 t CO_2), which are also developing countries. However, they are much lower than the values of Russia (5.9 t CO_2) and other developed countries such as Japan (6.6 t CO_2), the UK (5.7 t CO_2), Germany (6.4 t CO_2) and the USA (10.4 t CO_2, Table 4). This may be the main reason that Nanchang or China is still an underdeveloped economic entity when compared to the developed economic entities in the western world from a global perspective.

Similarly, when only considering the CEs of the entrance and kernel, the CE per GDP of household consumption is equivalent to the middle level of urban China (0.216 < 0.221 <0.222 t $CO_2/10^4$ Yuan). This result shows again that the accounting process of household

Table 4 | Total population, per capita CE and CE per GDP of the household consumption system from different regions or countries

	Total population (10^6)	CE per capita (t CO_2)	CE per GDP (t $CO_2/10^4$ Yuan)
Nanchang total	5.18[a]	1.35[a]	0.232[a]
Nanchang[b]	5.18[a]	1.28[a]	0.221[a]
China, total	1,354	1.72	0.227[c]
Urban China, total	712	2.44	0.220[c]
Very rich	71	6.39	0.223[c]
Rich	71	3.73	0.219[c]
Middle-high	142	2.75	0.220[c]
Middle	142	2.00	0.216[c]
Lower-middle	142	1.49	0.218[c]
Poor	71	1.12	0.222[c]
Very poor	36	0.75	0.226[c]
Extremely poor	36	0.58	0.225[c]
Rural China, total	642	0.93	0.256[c]
Highest	128	1.64	0.257[c]
Middle-high	128	1.07	0.256[c]
Middle	128	0.79	0.254[c]
Poor	128	0.62	0.250[c]
Extremely poor	128	0.51	0.254[c]
India	1,247	0.9	0.242[c]
Brazil	193	1.5	0.049[c]
Russia	143	5.9	0.226[c]
Japan	127	6.6	0.060[c]
UK	63	5.7	0.054[c]
Germany	80	6.4	0.062[c]
EU27	500	6.7	0.080[c]
USA	312	10.4	0.075[c]

[a]The calculated results of our article in 2014 and the other results are from 2012.
[b]Only contains the CEs of the entrance and kernel of the household consumption system.
[c]The values are in 2012 and calculated according to the results of the article by Wiedenhofer *et al.* (2017). The other data without superscript symbols were directly obtained from the same article.

consumption CEs is accurate and reliable. Moreover, the results are also consistent with the reality of social and economic development in Nanchang. In addition, the results are closer to the values of India (0.242 t $CO_2/10^4$ Yuan) and Russia (0.226 t $CO_2/10^4$ Yuan), which are also developing countries. However, there is a large difference compared to the values of Brazil (0.049 t $CO_2/10^4$ Yuan) and other developed countries such as Japan (0.060 t $CO_2/10^4$ Yuan), the UK (0.054 t $CO_2/10^4$ Yuan), Germany (0.062 t $CO_2/10^4$ Yuan) and the USA (0.075 t $CO_2/10^4$ Yuan, Table 4). This shows that Nanchang should vigorously promote the efficiency of household energy use to reduce the corresponding values of CE per GDP in the home, when compared to the western developed economic entities.

Nevertheless, it is noteworthy that the CE per GDP of Nanchang's household consumption was decreasing. As shown in Figure 7, when considering the CEs of the systematic outlet (landfills and wastewater treatment), the CE per GDP was 0.293 t $CO_2/10^4$ Yuan in 1998, and it decreased to 0.232 t $CO_2/10^4$ Yuan in 2014, by an annual average amount of −0.004 t $CO_2/10^4$ Yuan and at a rate of −1.45%. When only considering the CEs of the entrance and kernel, the CE per GDP was 0.280 t $CO_2/10^4$ Yuan in 1998, and it decreased to 0.221 t $CO_2/10^4$ Yuan in 2014, by the same annual average amount and at a rate of −1.47%. These changes may be mainly arising from the reality that people have increasingly emphasized energy conservation and the maintenance of thrifty and efficient lifestyles. Another reason is that at the same time local government has also put forward some strategies and countermeasures to promote low carbon development of society.

However, with economic development and improvement in life standards, a large number of energy-intensive lifestyles and behavioural habits were increasingly growing.

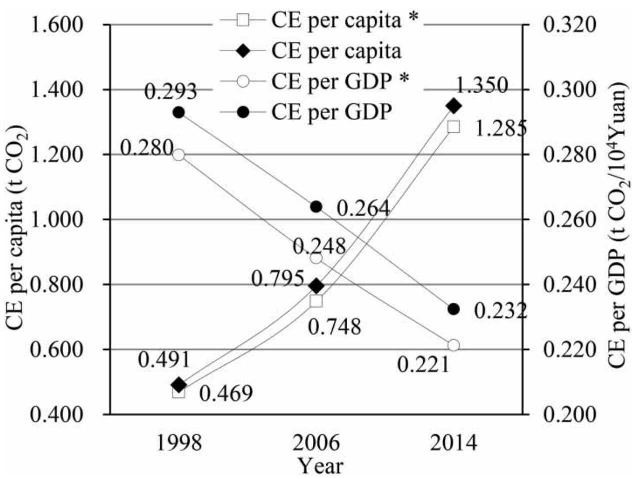

Figure 7 | The per capita CE and CE per GDP of Nanchang's household consumption system from 1998 to 2014 (* only contains the CEs of the entrance and kernel).

Thus, the CEs per capita of household consumption were also growing. The specific data are shown in Figure 7. For example, when considering the CEs of the systematic outlet (landfills and wastewater treatment), the CE per capita was only 0.491 t CO_2 in 1998, but it increased quickly to 1.350 t CO_2 in 2014, by an annual average increasing amount of 0.054 t CO_2 and at a rate of 6.53%.

Uncertainties and applicability

Taking a typical underdeveloped city, Nanchang in China, as an example, we put forward a new accounting frame (methodology) of household consumption CEs to incorporate the landfill and wastewater treatment items as the outlet of the household consumption system. The results proved that it is feasible, credible and effective for assessing the sustainability of household consumption behaviour. However, similar to other methods, this methodology is also subject to some uncertainties. In the article, the main uncertainties may be rooted in the following. First, the emission factors of different kinds of energy and products may have some inherent uncertainties. For example, we directly adopt the related data of China in the IEA statistics or the IPCC. The emission factors of electricity are directly from the IEA. The other factors are mainly from the IPCC. Especially in CE calculation of landfills and domestic wastewater treatment, default emission factors are often used. Second, the calculation model may have some unpredicted and systematic errors, such as the IPCC-recommended FODM. This FODM is used to calculate solid waste CEs from a global point of view. However, the decay speed and mode of the solid waste may vary as influencing factors change, such as time, place and climate. In other words, the model may be different from the actual situation in Nanchang. In addition, the lack of some data sources may make the calculated result for Nanchang less than that of the reality. For example, we calculate the direct CEs of only four household energy uses: coke oven gas, natural gas, LPG and electricity. The result may be less than the real emissions from all household energy uses in Nanchang. Similarly, we calculate the direct CEs of only three personal travel modes, private cars, motorcycles and steering wheel tractors, which may also make the results lower than those of reality.

However, the new accounting methodology of household consumption CEs can at least provide us with some new knowledge from a systematic perspective and some reliable strategies or countermeasures for sustainable household consumption behaviour. On the other hand, the new method can also be used in other areas as long as the related basic data of the area's wastewater treatment, etc., can be obtained. These areas can be any provinces or cities, especially near the Poyang Lake Ecological-Economic Zone in Jiangxi Province, China.

CONCLUSIONS AND POLICY IMPLICATIONS

Taking Nanchang in China as an example, we construct a new frame or methodology by incorporating the CEs of domestic wastewater treatment and landfills into an emission inventory of household consumption to better explain household consumption behaviour from a systematic perspective. The new methodology contains three accounting sections: entrance (lifestyles), kernel (home energy uses and private vehicles) and outlet (landfills and domestic wastewater treatment).

All in all, we find that all the CEs of the entrance, kernel and outlet had an increasing trend during the study period of 1998–2014. They were, respectively, 172.65×10^4 t CO_2, 22.19×10^4 t CO_2 and 9.18×10^4 t CO_2 in 1998. In 2006, they increased to 283.10×10^4 t CO_2, 78.83×10^4 t CO_2 and 23.03×10^4 t CO_2. In addition, in 2014, they subsequently increased to 458.43×10^4 t CO_2, 206.82×10^4 t CO_2 and 33.55×10^4 t CO_2. The CE shares of the three sections were 66%–85%, 11%–30% and 4–6%, respectively. The entrance's share among all the sources of CEs was always decreasing, and the kernel was invariably increasing. However, the outlet's share had an initially increasing and then decreasing trend.

Although the CE shares of wastewater treatment and landfills are modest now, they are not negligible and still have a certain importance, and they will most likely become increasingly greater in the future for three important reasons. Therefore, it was necessary and significant for us to incorporate the CEs of wastewater treatment and landfills into the household emission inventory in this paper. The results also show that the new frame is accurate and reliable.

It can help in obtaining more scientific data on emission reduction and regional sustainable consumption, especially for analysing household consumption behaviour. Similar to any other method, some uncertainties exist in this frame, but the new accounting methodology of household consumption CEs provides an undeniable perspective of knowledge and effectiveness and can also be used in other areas as long as the related basic data of an area's wastewater treatment, etc., can be obtained.

Based on these results, some policy implications for sustainable household consumption are put forward and listed as follows.

First, for the entrance CEs, clothing, food, residence, education, and cultural and recreation services were the major sources. All the other sources' CEs contributed only 5–8% of the entrance CEs from 1998 to 2014. Thus, we should pay much attention to reduce these lifestyle CEs for a healthier system of Nanchang household consumption. For example, we should wear simple clothing, design houses in a low-carbon style, avoid wasting food, conserve paper, etc., as much as possible.

Second, the kernel CEs were the next largest share of the total CEs from the household consumption system. Moreover, the CEs of private vehicles had the fastest growth rate among all the CE sources of the household consumption system. Thus, we should try to conserve direct energy consumption in family life. In particular, we should try our best to improve the efficiency of the fuel combustion of private cars. For example, we could encourage a city's residents, especially private car owners, to drive less and choose walking or public transportation such as buses, subways, etc., to commute to work as much as possible.

Third, the CE shares of wastewater treatment and landfills are currently modest, but they are not negligible and still have a certain importance, especially in the future. From this perspective, we should complement and improve the current lack of some statistical data. Then, we should unceasingly strengthen the science and rationality of statistical work. For example, population-related data with or without registration information should be disclosed and annotated in as much detail as possible. Moreover, we could search for some more scientific and reasonable methods to calculate the CEs of wastewater treatment, etc., so that the results are closer to reality. Last but not least, in the long run, we should institutionalize this work of accounting for domestic wastewater treatment and landfills in order to highlight the importance of this work and help people form better habits of waste management.

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