Supporting Information for: Tracing the consumption origins of wastewater and sludge for a Chinese city based on waste input-output analysis

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1 The current state of wastewater and sludge treatment in China

China has the second-highest wastewater treatment capacity in the world [1], with 5222 wastewater treatment plants to treat 2.28×10^8 m^3 wastewater every day in 2018. The sludge in China was 11.7 million tons in 2018, with an average annual growth rate of 10% from 2011-2018. Sludge is treated by landfilling (50%), incineration (10%), materials recycling (9%), and composting (16%)[1]. Although landfills accounted for the largest part of sludge treatment, it is not a favorable solution in the future. The water content of the sludge for landfills should be less than 60% after 2007 [2]. As a result, a large amount of landfilled sludge cannot meet the new requirements and thus is disposed of improperly[3]. Given that 80% of landfills cannot meet the national standard, only about 45% of the sludge is properly treated at present.

Sludge for land use and incineration have been recommended as the best available technologies[4]. Sludge treatment should be compatible with technology, economic development level, and environmental management requirement for different application conditions. Furthermore, the zero-waste city plan further proposed to minimize the amount of landfills and ultimately realize the full utilization of waste[5]. In 2020, The latest revision of the Solid Waste Prevention and Control Law confirmed that sludge treatment facilities should be incorporated into the urban wastewater treatment plan. China is in a transition period with respect to wastewater and sludge management from end-pipe disposal to waste-to-resource management.

2 Methodology

2.1 The W^2IO model

2.1.1 Derivation of equation

A hybrid IO model was produced to examine both the generation and treatment of wastewater, as an extension of the WIO in Nakamura and Kondo (2009)[6]. The framework of W^2IO is presented in Table S1. Let there be n producing sectors, k waste/wastewater treatment sectors, and m types of waste/wastewater. The n×n matrix, $\mathrm{X_P}$, refers to the intermediate input flows in the economic (goods and services producing) sectors, the n×k matrix $\mathrm{X_T}$ to the input from the economic sectors to the treatment sectors, the n×f matrix $\mathrm{Y_P}$ to the final demand for goods and services, the k×f matrix $\mathrm{Y_w}$ to the final demand for wastewater, sludge and ash, and $\mathrm{W_P}$ and $\mathrm{W_T}$ to the direct flows of wastewater, sludge and ash resulting from the producing and treatment sectors, respectively. The n×1 vector x_P refers to the activity levels of economic sectors, and the k×1 vector, x_T, the activity level of wastewater treatment sectors.

Table S1 includes three wastewater treatment processes, namely, oxidation ditch (OD), anaerobic/anoxic/oxic(A2/O) processes, and biological aerated filter (BF), two dewatering processes, i.e., mechanical dewatering with centrifugal dewatering equipment (hereafter termed Dew 80) that reduces water content from 96% to around 80%, and plate-frame pressure filtration (hereafter termed Dew 60) that combines mechanical dewatering with chemical methods and reduces the water content to below 60%, and three types of sludges, which are raw sludge (Sludge 90) from the wastewater treatment process with water content above 90%, Sludge 80 with water content less than 80% obtained by subjecting Sludge 90 to Dew 80, and Sludge 60 with water content less than 60% obtained by subjecting Sludge 90 to Dew 60. The treatment options for dewatered wet sludge include landfill, incineration, and composting.

Table S1 Framework of the W²IO table

	Economic sectors		Wastewater treatment sectors (k)							Final demand (f)				Output
Economic sectors	Production sectors(n)	Compost	Wastewater treatment			Sludge treatment				Consumption	Capital formation	Government expenditure	Export	
	1,2 …139		A2O	OD	BAF	Dew 1	Dew 2	Landfill	Incineration					
1	X_P		X_T							Y_P				x_P
2														
…														
139														
Compost														
Waste/wastewater (m)														
Wastewater (t)	W_P		W_T							Y_W				x_W
Sludge 90 (t)														
Sludge 80 (t)														
Sludge 60 (t)														
Ash (t)														

The balancing equations of products and waste are given by:

$$\sum_{j=1}^{n}(X_P)_{ij} + \sum_{j=1}^{k}(X_T)_{ij} + \sum_{j=1}^{k}(Y_P)_{ij} = (x_P)_i \quad \text{(S1)}$$

$$\sum_{j=1}^{n}(W_P)_{ij} + \sum_{j=1}^{k}(W_T)_{ij} + \sum_{j=1}^{k}(Y_W)_{ij} = (x_W)_i \quad \text{(S2)}$$

The matrix of input coefficients, A's, and wastewater generation coefficients, G's, are given by:

$$A_P = X_P\widehat{x_P}^{-1},\ A_T = X_T\widehat{x_T}^{-1},\ G_P = W_P\widehat{w_P}^{-1}, \text{and } G_T = W_T\widehat{w_T}^{-1},$$

where $\widehat{\ }$ refers to the diagonalized matrix of the variable it attaches. Using these matrices, (S1) and (S2) can be rewritten as:

$$\sum_{j=1}^{n}(A_P)_{ij}(x_P)_j + \sum_{j=1}^{k}(A_T)_{ij}(x_T)_j + \sum_{j=1}^{k}(Y_P)_{ij} = (x_P)_i \quad \text{(S3)}$$

$$\sum_{j=1}^{n}(G_P)_{ij}(x_P)_j + \sum_{j=1}^{k}(G_T)_{ij}(x_T)_j + \sum_{j=1}^{k}(Y_W)_{ij} = (x_W)_i \quad \text{(S4)}$$

or using matrix notations as:

$$\begin{pmatrix} A_P & A_T \\ G_P & G_T \end{pmatrix}\begin{pmatrix} x_P \\ x_T \end{pmatrix} + \begin{pmatrix} y_P \\ y_W \end{pmatrix} = \begin{pmatrix} x_P \\ x_W \end{pmatrix} \quad \text{(S5)}$$

This system is not solvable, because of the asymmetry; wastewater occurs on the right-hand side, while the levels of wastewater treatment occur on the left-hand side [7-8]. While the original form of (S5) is not solvable because of this reason, it can be transformed into a solvable symmetric one by establishing the allocation of different types of wastewater to different wastewater treatment processes [7] This allocation is represented by the allocation matrix *S* of order $k \times m$, where its *i-j* element S_{ij} refers to the share of waste *j* that is allocated to the treatment process *i*.

By use of S, (S5) is transformed to a symmetric system in terms of goods production and wastewater treatment:

$$\begin{pmatrix} A_P & A_T \\ SG_P & SG_T \end{pmatrix}\begin{pmatrix} x_P \\ x_T \end{pmatrix} + \begin{pmatrix} y_p \\ Sy_w \end{pmatrix} = \begin{pmatrix} x_P \\ Sx_W \end{pmatrix} = \begin{pmatrix} x_P \\ x_T \end{pmatrix} \quad \text{(S6)}$$

where $x_T = Sx_W$ refers to the output of waste treatment sectors, i.e., the amount of waste treated, with the solution:

$$\begin{pmatrix} x_P \\ x_T \end{pmatrix} = \begin{pmatrix} I - A_P & -A_T \\ -SG_P & I - SG_T \end{pmatrix}^{-1} \begin{pmatrix} y_P \\ Sy_w \end{pmatrix} \quad \text{(S7)}$$

Finally, multiplication of G's from the left gives the m×n matrix referring to W^2F of products, W^2F_P, and $m \times t$ matrix referring to W^2F of direct discharge from final demand sectors, W^2F_w:

$$(W^2F_P \;\; W^2F_w) = (G_P \;\; G_T)\begin{pmatrix} I - A_P & -A_T \\ -SG_P & I - SG_T \end{pmatrix}^{-1} \begin{pmatrix} \widehat{y_P} & 0 \\ 0 & \widehat{Sy_w} \end{pmatrix} \qquad (S8)$$

2.1.2 Adjusting for imports

The flows of goods and waste in the Xiamen IO table include imports from other provinces and abroad. A straight application of the above footprint calculation without considering this fact could result in overestimating the footprints on Xiamen because the imports are not produced in Xiamen. To deal with this issue, we adjusted the flows for imports along the Chenery–Moses model [9]. Denoting by y_{Import} the vector of imports, we define the share of import of a product in its total supply, m_i, as:

$$m_i = y_{Import}/(x_P + y_{Import}) \tag{S9}$$

With the import share thus defined, y_P, in (S7) is adjusted for imports by:

$$y_{Pd} = \widehat{(1-m)} \sum y_P$$

resulting in equation (3) in the text. The corresponding adjustment for the flow of waste/wastewater was not necessary because of the absence of imports. With m_i and y_{Pd} thus obtained, (2) is adjusted for imports as:

$$(W^2F_P \quad W^2F_w) = (G_P^* \quad G_T^*) \left[\left(I - (I - \widehat{m})\right) \begin{pmatrix} A_P & A_T^* \\ SG_P^* & SG_T^* \end{pmatrix} \right]^{-1} \begin{pmatrix} \widehat{y_{Pd}} & 0 \\ 0 & \widehat{Sy_W} \end{pmatrix}$$

(S10)

2.2 The W²IO table and other data

2.2.1 Production sector classification

The IO table in Xiamen contains 139 sectors (Table S2), with a water supply and production aggregated with wastewater treatment.

Table S2 Production sector classification: Xiamen IO table

	Sector		Sector
1	Crop cultivation	37	Printing and record medium reproduction
2	Forestry	38	Cultural, sporting and recreational products
3	Livestock and products	39	Petroleum refining and nuclear fuel
4	Fishery	40	Coking
5	Technical services for agriculture	41	Raw chemical materials
6	Coal mining and processing	42	Chemical fertilizers
7	Crude petroleum and natural gas	43	Chemical pesticides
8	Ferrous metal ore mining	44	Chemicals for painting, dying and others
9	Non-ferrous metal ore mining	45	Synthetic chemicals

10	Non-metallic minerals and other mining	46	Chemicals for special usages
11	Mining auxiliary services and other mining products	47	Surfactant Detergent & Cosmetics
12	Grain mill products	48	Medical and pharmaceutical products
13	Feeding stuff production	49	Chemical fibers
14	Vegetable oil and forage	50	Rubber products
15	Sugar refining	51	Plastic products
16	Slaughtering and meat processing	52	Cement, lime and gypsum
17	Prepared fish and seafood	53	Cement products and other similar products
18	Vegetable, fruit and nut processing	54	Brick, tile, stone and other building materials
19	Convenient foods	55	Glass and glass products
20	Liquid milk and dairy products	56	Ceramic products
21	Spices and fermentation products	57	Fireproof products
22	Other food manufacturing	58	Other non-metallic mineral products
23	Wines, spirits and liquors	59	Iron smelting
24	Non-alcoholic beverage	60	Steel smelting
25	Tobacco products	61	Iron alloy smelting
26	Cotton textiles	62	Nonferrous metal smelting
27	Woolen textiles	63	Nonferrous metal processing
28	Hemp textiles	64	Metal products
29	Finished textile products	65	Boiler, engines and turbine
30	Knitted mills	66	Metalworking machinery
31	Wearing apparel	67	Lifting transport equipment
32	Leather, furs, down and related products	68	Pump, valve, compressor and similar machinery
33	Shoes	69	Culture, office machinery
34	Sawmills, fiberboard, and products of wood, bamboo, cane, palm, straw, etc.	71	Mining, metallurgy and construction equipment
35	Furniture	72	Chemical engineering, wood and non-metallic processing equipment
36	Paper and paper products	73	Cultivation, forestry, animal husbandry and fishery machinery

	Sector		Sector
74	Other special equipment	108	Tube transportation
75	Motor vehicles	109	Service agent
76	Components for vehicles	110	Warehousing
77	Railroad transport equipment	111	Post
78	Ship building	112	Hotel
79	Other transport machinery	113	Eating and drinking places
80	Generators	114	Telecommunication

81	Power transmission, distribution and control equipment	115	Software
82	Cable and electrical materials	116	Finance
83	Battery	117	Financial market
84	Household appliances	118	Insurance
85	Other electric machinery and equipment	119	Real estate
86	Electronic computer	120	Leasehold
87	Communication equipment	121	Business services
88	Radar and broadcasting equipment	122	Scientific research and experiment
89	Household audio-visual equipment	123	Special technical services
90	Electronic elements and devices	124	Science & technology exchange and promotion services
91	Other electronic equipment	125	Water conservancy
92	Instruments and measuring equipment	126	Environmental management
93	Other manufactured products	127	Public infrastructure management
94	Scrap and waste recycling	128	Residential services
95	Repair of metal products and machinery	129	Other social services
96	Electricity and heat production and supply	130	Education services
97	Gas production and supply	131	Health services
98	Water production and supply	132	Social welfare
99	Construction	133	News press
100	Civil engineering	134	Radio, television, film and audio-video
101	Installation	135	Culture and arts
102	Decoration	136	Sports
103	Wholesale and retail trade	137	Recreational services
104	Railway transportation	138	Social security
105	Road transportation	139	Public administration and social organization
106	Water transportation		
107	Air transportation		

2.2.2 Correction of the original IO data with RAS

In the original IO table of Xiamen, “Road transport" ranks as the second-largest intermediate user (365.57 million RMB) of "Crop cultivation" after "Vegetable oil and forage" (624.79 million RMB). However, the corresponding entry in the National IO tables for China was 0 for both the 2012 and 2017 tables. Furthermore, we were not able to find any local data supporting the presence of this large transaction. Accordingly, footprint calculation based on the original IO table produced results that are difficult to interpret. We, therefore, decided to replace the entry of this cell with zero. To maintain consistency in the accounting of the resulting IO table, the matrix of input coefficients was subjected to adjustments by the RAS method [9].

2.2.3 Data used to develop the W^2IO table for Xiamen

The data in Panel A of "Treatment", excluding sludge landfill and incineration, were obtained from XEPB (2012)[10]. For sludge incineration and landfilling, the corresponding data on municipal solid waste was used. The data on sludge composting was obtained from the actual operation data of sludge composting. Using data on investment expenditure and operating costs of WWTPs [10], we extracted the data on wastewater treatment separately from the IO table.

The data on wastewater and COD in Panel B of "Production" was obtained from XPSO (2011)[11]. Agriculture is a non-point source of pollution. Agricultural cultivation and fisheries are not included in the domestic sewage pipe network. Only a small amount of large-scale farming wastewater enters the WWTP pipeline. The data on wastewater treatment capacity, sludge generation, and COD were obtained from the annual operation data provided by the Xiamen Municipal Construction Group. Finally, the data on wastewater and COD in Panel B of "Final demand" was obtained from CCNPS (2011)[12], a booklet that gives the factors for wastewater generated by residents in China, divided into five major categories. Xiamen city belongs to the first category of the second district in China and is in the same category as Shanghai, Guangzhou, and Hangzhou.

Table S3 The allocation matrix S of waste/wastewater to treatment processes

	Waste/wastewater				
Treatment	Wastewater	Sludge 90	Sludge 80	Sludge 60	Ash
A2O	0.19	0.00	0.00	0.00	0.00
OD	0.43	0.00	0.00	0.00	0.00
BF	0.38	0.00	0.00	0.00	0.00
Dewater80	0.00	0.36	0.00	0.00	0.00
Dewater60	0.00	0.64	0.00	0.00	0.00
landfill	0.00	0.00	0.00	0.89	1.00
Incineration	0.00	0.00	1.00	0.11	0.00

Table S4 The W[2]IO table of Xiamen based on the framework in Table 1.

			Production				Treatment							Final demand
			Primary	Secondary	Tertiary	Compost	A2O	OD	BF	Dew80	Dew60	Landfill	Incineration	
production	Primary	Panel A	37593	533884	36901	0	0	0	0	0	0	0	0	888910
	Secondary		64679	31228532	3346075	126	2033	4529	4094	272	1517	10	974	50110665
	Tertiary		57494	9060617	9544181	0	277	638	554	0	0	0	0	8533767
	Compost		98	0	0	0	0	0	0	0	0	0	0	0
wastewater/waste	wastewater	Panel B	1	3024	3153	0	0	0	0	0	0	2	0	14903
	sludge 90		0	0	0	0	203604	509028	343604	0	0	0	0	0
	sludge 80		0	0	0	-30080	0	0	0	47054	0	0	0	0
	sludge 60		0	0	0	0	0	0	0	0	75723	0	0	0
	ash		0	0	0	0	0	0	0	0	0	0	5090	0
Effluents	COD		4	8896	7472	0	1326	2309	2742	0	0	2	0	50669
Treatment	A2O	Part C	0	562	585	0	0	0	0	0	0	0	0	2767
	OD		0	1312	1368	0	0	0	0	0	0	1	0	6466
	BF		0	1150	1199	0	0	0	0	0	0	1	0	5669
	Dew80		0	0	0	0	72809	182028	122873	0	0	0	0	0
	Dew60		0	0	0	0	130795	327000	220731	0	0	0	0	0
	landfill		0	0	0	0	0	0	0	0	67242	0	5090	0
	Incineration		0	0	0	-30080	0	0	0	47054	8481	0	0	0

Units: 10^3kg for sludge, ash and COD, 10^7 kg for wastewater, and 10 k RMB for the monetary flows in the "industry" rows. The latter include imports. The bottom panel (Panel C) gives the flow of waste/wastewater converted to the flow of treatment via allocation matrix in Table S2.

The upper panel (Panel A) represents the flow of goods and services during production, wastewater/waste treatment sectors, and the final demand in monetary units, whereas the middle panel (Panel B) with the rows referring to waste/wastewater represents the flow of waste/wastewater generated in physical units. Panel C gives the flow of waste/wastewater converted by the allocation matrix S in Table S2 to the flow among treatment sectors. This converts wastewater discharges into inputs of wastewater treatment services, the generation of raw sludge from wastewater treatment sectors into the generation of dewatering activities, the generation of dewatered sludge into the inputs of incineration and landfill, and the input of sludge into composting as a negative input of incineration because the sludge is incinerated when not recycled as compost.

For instance, of 30 Mt of wastewater discharged from secondary sectors, 11.5 Mt is sent to BF, 13 Mt to OD, and the rest to A2O. Of the 203 kt of raw sludge generated by A2O, 13 kt (64%) is sent to Dew 60, with the rest being sent to Dew 80. Approximately 89% of Sludge 60 is landfilled, with the rest being directly incinerated. A sizable amount (64%) of Sludge 80 is used (recycled) in the composting sector as represented by its negative output in the sector. As Sludge 80 is otherwise incinerated (Table S3), its recycling in the form of composting and subsequent use as a substitute for fertilizers in the agricultural sector leads to a reduction in the amount of incinerated Sludge 80. This is represented in the bottom panel referring to treatment by the occurrence of a negative input of incineration in the composting sector. If not recycled, Sludge 80 would be incinerated (Table S3), leading to the generation of 5 kt of ash, which would then be landfilled.

2.2.4 COD from different sources of wastewater discharge

Table S5 COD and wastewater discharge

	Toilet	Kitchen	Bath-wash	Source
COD (kg/y) EU	27.5	16	3.7	Ref 13
Wastewater (m^3/y) EU	19	18	18	Ref 13
Wastewater (m^3/y): Singapore	24	33	88	Ref 14
COD (kg/y) Xiamen	12.76	17.64	5.44	EU value Ref 13
Wastewater (m^3/y) Xiamen	8.82	19.84	26.46	Singapore share Ref 14

Due to the lack of Chinese data on COD by sources of wastewater discharge, we used the EU data on COD concentration of wastewater from toilets, 27.5/19 =1.45 kg/m^3, provided by [13] Henze et al. (2002, Table 1.17). As for the share of wastewater discharge by sources, we used the data on Singapore (16% for toilet) taken from JWRC (2018) [14] instead of the EU value. This choice was made considering the similarity between Xiamen and Singapore in terms of the climatic zone and diet patterns. This resulted in the estimated share for Xiamen of toilet wastewater in total COD of 0.36.

2.2.5 Diet pattern, toilet discharge, and carbon content of food

Table S6 Data on food (diet, toilet discharge, and carbon content)

	Food consumption	Toilet discharge	Carbon content	Spanish diet
Units	kg/p/y	l/kg	100g-C/g-food	kg/p/y
Source	Ref 15	Ref 16	Ref 17	Ref 16
Grain mill products	41.9	20.5	32.7	41.9
Vegetable oil and forage	8.9	20	76.7	22
Slaughtering and meat processing	43.4	25	25.5	66
Prepared fish and seafood	18.1	25.5	14.3	37
Vegetable, fruit, and nut processing	160.5	24	5.0	225
Liquid milk and dairy products	12.8	25	6.3	143
Other food manufacturing	6.4	19.5	32.7	6.4
Wines, spirits and liquors	6.7	24	4.1	6.7
Non-alcoholic beverage	2.7	24	4.1	2.7

2.3 Scenario analysis

Two scenarios were considered to assess the effects of possible changes in industrial structure and diet patterns. The first one (Scenario 1) is based on the rate of industrial growth prescribed in the 13th Five-Year Plan for economic and social development in Xiamen city. In that plan, sectors such as electronic information and mechanical manufacturing are expected to play a vital role in economic growth, with the output of electronic information expected to increase from 0.3 trillion RMB in 2015 to 0.7 trillion RMB in 2020, or a 2.3-fold increase. To assess the impacts of planned industrial growth, we evaluated the effects on wastewater and sludge of the same 2.3-fold increase in the final demand for the products of 15 manufacturing sectors consisting of cars, ships, machinery, electronics, computer, and communication equipment. Denoting by DW_{S1}, $W2F_{S1}$, and $W2F_{S1}$ the direct wastewater discharge, wastewater footprint, and sludge footprint under Scenario 1, respectively, we have

$$DW_{S1} = \sum_i r_i \times DW_i \tag{S11}$$

$$W2F_{S1} = \sum_i r_i \times W2F_i \tag{S12}$$

$$SF_{S1} = \sum_i r_i \times SF_i \tag{S13}$$

where r_i refers to the expected rate of change in the output of sector *i*.

The second scenario (Scenario 2) refers to a possible shift in diet from the traditional Chinese one mostly based on staples toward a European (Spanish) one involving larger amounts of animal-sourced foods. The evaluation was carried out by altering the consumption of "Vegetable oil and forage" "Slaughtering and meat processing", "Prepared fish and seafood", "Vegetable, fruit and nut processing," and "Liquid milk and dairy products" to the Spanish level (the last column of Table S3), and applying the same calculation as in Scenario 1.

2.4 Sensitivity analysis

To examine the robustness of the results, we conducted a sensitivity analysis for key parameters based on the sensitivity elasticity of parameters [18-19], which indicates the ratio by which a change in "key parameters" changes the results, W^2F and SF in our case. The elasticity is given by

$$\mathrm{EL} = \frac{\partial y}{\partial a} \times \frac{a}{y} \tag{S14}$$

where $\boldsymbol{y}$ denotes W^2F or SF and $\boldsymbol{a}$ the parameter under study. Among others, $\boldsymbol{\theta_i}$ and $\boldsymbol{\alpha_j}$ are considered as key parameters.

3 Results

3.1 Direct discharge versus footprint

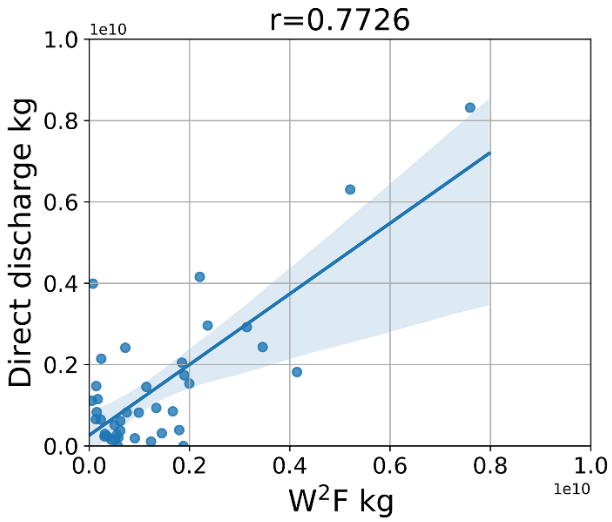

Figure S1 Direct discharge versus W^2F of the largest 40 sector

3.2 Wastewater and sludge footprint by final demand categories

In terms of final demand categories, the largest share of W^2F (42%) is attributed to export, followed by urban household consumption (33%). The largest share of SF (78%) is attributed to urban household consumption, followed by export (10%) (Figure S2).

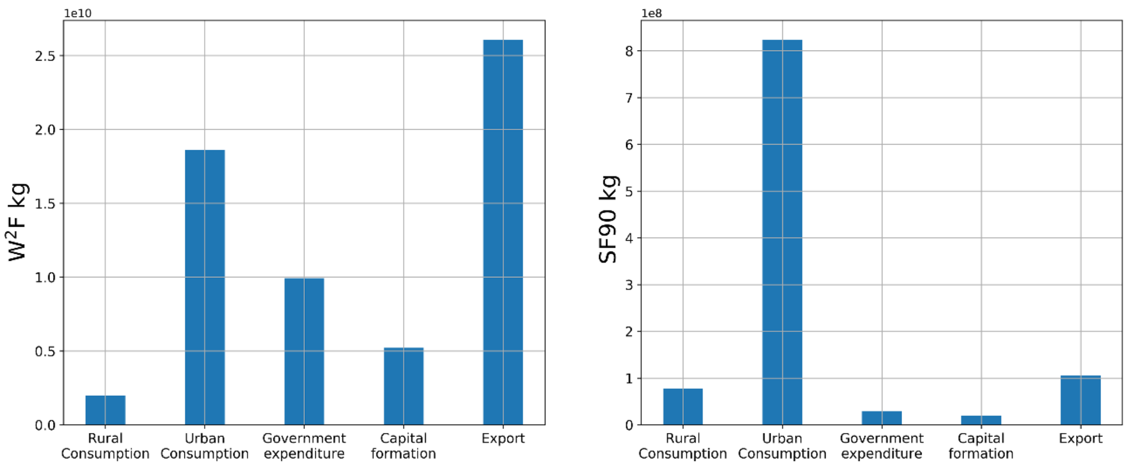

Figure S2 Wastewater and sludge footprint by final demand categories

3.3 Sensitivity analysis

3.3.1 The sensitivity of pre-consumption W^2F and SF to input and waste generation coefficients

Table S7 shows input and wastewater generation coefficients elasticities of pre-consumption W^2F and SF, and gives the ratio by which a change in relevant coefficients changes W^2F or SF. For instance, the value 0.000003 at the upper-left cell shows that a one % change in the input coefficient of electricity of the composting process changes the wastewater footprint by 0.000003, that is, practically no impact. The results indicate that for most cases the elasticities are small, with the occurrence of large elasticities concentrated to sludge generation coefficients. The largest one, 2.77, refers to the effects on sludge80 footprint of the sludge90 generation coefficients of Dew80, Dew60, landfill, and incineration treatment processes. It implies that a one % change in the coefficient change would induce a 2.77% change in SF of sludge80. Since these coefficients were directly obtained from data on the real operation of WWTPs in the city, they are of high reliability, implying the robustness of our results of SF.

Table S7 Sensitivity elasticity of pre-consumption W^2F and SF to input and waste generation coefficients

Coefficients	Footprint	Wastewater	Sludge90	Sludge80	Sludge60
Electricity	Compost	0.000003	0.000000	0.000002	0.000001
	A2O	0.000037	0.000000	0.000029	0.000011
	OD	0.000082	0.000000	0.000066	0.000024
	BF	0.000068	0.000000	0.000055	0.000020
	Dew80	0.000002	0.000000	0.000002	0.000001
	Dew60	0.000004	0.000000	0.000003	0.000001
	Landfill	0.000000	0.000000	0.000000	0.000000
	Incineration	0.000002	0.000000	0.000001	0.000001
Wastewater	Compost	0.000000	0.000000	0.000000	0.000000
	A2O	0.000000	0.000000	0.000000	0.000000
	OD	0.000000	0.000000	0.000000	0.000000
	BF	0.000000	0.000000	0.000000	0.000000

	Dew80	0.000000	0.000000	0.000000	0.000000
	Dew60	0.000000	0.000000	0.000000	0.000000
	Landfill	0.000280	0.000000	0.000000	0.000000
	Incineration	0.000280	0.000000	0.000227	0.000082
Sludge90	Compost	0.000000	0.000000	0.000000	0.000000
	A2O	0.000000	0.192764	0.000000	0.000000
	OD	0.000062	0.481927	0.534416	0.192783
	BF	0.000216	0.325310	1.870517	0.674760
	Dew80	0.000321	0.000000	2.772421	1.000108
	Dew60	0.000321	0.000000	2.772421	1.000108
	Landfill	0.000321	0.000000	2.772421	1.000108
	Incineration	0.000321	0.000000	2.772421	1.000108
Sludge80	Compost	0.000000	0.000000	-1.772122	0.000000
	A2O	-0.000026	0.000000	-1.772143	-0.000007
	OD	-0.000026	0.000000	-1.772143	-0.000007
	BF	-0.000026	0.000000	-1.772143	-0.000007
	Dew80	-0.000026	0.000000	0.999976	-0.000007
	Dew60	0.000015	0.000000	1.000013	0.000004
	Landfill	0.000015	0.000000	1.000013	0.000004
	Incineration	0.000015	0.000000	1.000013	0.000004
Sludge60	Compost	0.000000	0.000000	0.000000	0.000000
	A2O	0.000000	0.000000	0.000000	0.000000
	OD	0.000000	0.000000	0.000000	0.000000
	BF	0.000000	0.000000	0.000000	0.000000
	Dew80	0.000000	0.000000	0.000000	0.000000
	Dew60	0.000000	0.000000	0.000000	1.000000
	Landfill	0.000267	0.000000	0.000217	1.000090
	Incineration	0.000267	0.000000	0.000217	1.000090

Note: The first and second columns show the names of input and waste generation coefficient. The first row show the names of wastewater and sludge footprints.

3.3.2 The sensitivity of post-consumption W^2F and SF to key parameters

Table S8 shows the sensitivity elasticities of post-consumption W^2F and SF to key parameters, θ_i and α_j. The first block shows the effects of a change in the discharge rate of toilet water associated with the excretion of food item i, that is, θ_i, on post-consumption WWF. For instance, the value 0.12 of the upper-left cell indicates that a one percent change in the amount of discharge of toilet water associated with the excretion of grain mill products results in a 0.12% change in the amount of post-consumption W^2F. The results indicate that the elasticities are rather small, with none exceeding 0.6. The largest value is observed for "Vegetable, fruits, and nut processing" on post SF, because of its largest share (53%) in the total mass food consumption.

The second block of Table S7 shows the impacts of a change in the ratio of raw sludge to total COD, α_j, of the three WWTPs on the amount of post-consumption W^2F. The results indicate that the amount of post-consumption W^2F is relatively sensitive to the parameter of OD treatment, which can be explained by that its treatment capacity is larger than the other two treatment processes. The parameter is obtained from annual WWTPs operation data in the city and hence is of high credibility, implying the robustness of our post-consumption SF results.

Table S8 Sensitivity elasticity of post-consumption W^2F and SF with respect to key parameters

Parameters	(Footprint)	Wastewater	Sludge90
θ_i	Grain mill products	0.12	
	Vegetable oil and forage	0.03	
	Slaughtering and meat processing	0.15	
	Prepared fish and seafood	0.06	
	Vegetable, fruit and nut processing	0.54	
	Liquid milk and dairy products	0.05	
	Other food manufacturing	0.02	
	Wines, spirits and liquors	0.02	
	Non-alcoholic beverage	0.01	
α_j	A2O		0.19
	OD		0.48
	BF		0.33

Note: The first and second columns show the parameters. The first row show the names of wastewater technology and sludge footprints.

3.4 Transboundary impacts

In the literature on carbon footprint based on multi-regional input-output (MRIO) analysis it is common to look at the impacts embodied in trade. While the current IO data is a single region one, it is possible to estimate the amounts of wastewater and sludge embodied in trade, assuming that the technology of the exporting countries is the same as that of Xiamen, that is, $\hat{m} = 0$ in (S10). The results in Table S9 indicate that Xiamen is a net exporter of wastewater and sludge, although the extent of "trade surplus" for the latter is much smaller. It is not the case that the city is keeping its own water resources clean at the expense of other regions of China.

Table S9 Wastewater and sludge embodied in trade

	Embodied in export	Embodied in import
Wastewater (10^7 kg)	6778	5813
Sludge90 (10^3 kg)	291741	274283

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