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Article

Tracing the Consumption Origins of Wastewater and Sludge for a Chinese City Based on Waste Input−Output Analysis

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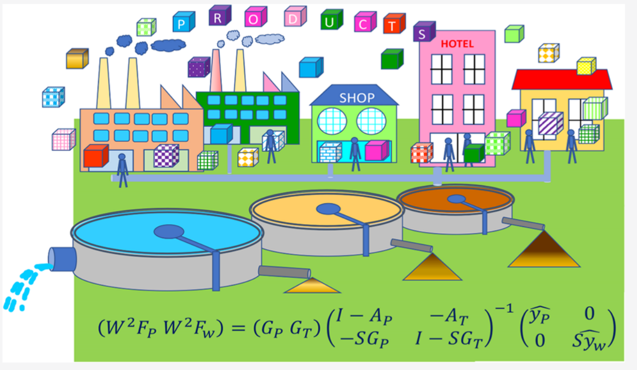
ABSTRACT: Water scarcity and pollution are grand challenges to sustainability. We developed a high-resolution wastewater input−output model for a Chinese city, Xiamen, incorporating detailed information on the treatment and quality of wastewater and sludge. We estimated consumption-based wastewater and sludge footprints of products (W^2F and SF, respectively). Significant differences were found between the amounts of direct discharge (scope 1) and W^2F (scopes 1−3), indicating the need to consider W^2F in making plans for future wastewater management strategies. Reflecting its high organic content, food-related consumption was found to be a significant contributor to sludge generation. Scenario analyses were conducted to assess the effects of a shift from the traditional Chinese diet to the European diet and the anticipated industrial growth.



Attempts were also made to establish links between the direct wastewater discharge of households and the final consumption of food items through human excretion, or the postconsumption footprints. It was found that the postconsumption W^2F outweighed the preconsumption W^2F for five out of nine food items, while the postconsumption SF outweighed the preconsumption SF in all cases except one. This research provides a scientific basis to identify the economy-wide fate of wastewater and sludge and to frame a policy for sustainable wastewater and sludge management.

1. INTRODUCTION

Wastewater treatment is at the core of public health. China has the second-highest wastewater treatment capacity in the world.[1] With the quantity of sewage sludge rapidly increasing, its treatment has become a challenging issue,[2] with 15% of sludge currently untreated and 55% not properly treated.[1,3] The conventional sludge disposal based on landfill and co-incineration has encountered increasing resistance from local municipalities. The environmental benefits of wastewater treatment would be diminished if the sludge were not treated appropriately.[4] Thus, there is an increasing need to track production and consumption activities to monitor the generation of wastewater and sludge and to propose a strategy for future wastewater and sludge management.

Water footprinting (WF) is widely used for assessing water-use-related environmental effects from the consumption of goods and services.[5] China's WF has been the subject of numerous studies.[6−15] The issues related to wastewater, however, do not seem to have attracted much attention in the WF literature. While gray WF refers to the volume of freshwater required to assimilate pollutants in wastewater and is sensitive to the background concentration of the surface water receiver,[16] it does not refer to the actual quantity of water consumed. Instead, it refers to a hypothetical quantity required to assimilate water pollution and is mostly used to show the economic burdens of water usage.[17] In other words, gray WF is not directly concerned with the volume of wastewater induced by final consumption and falls short of assessing the impacts of final consumption on sludge treatment.

To our knowledge, Lin[18] is the first study that addressed the issues of wastewater based on the waste input−output (WIO) model.[19−28] His wastewater IO model (W^2IO), developed for Tokyo, provides a link between wastewater generation, production sectors, and wastewater and sludge treatment sectors. However, the model lacks detailed information about sludge generation, composition, and treatment, which is necessary to identify the key polluting sectors and explore the potential for wastewater and sludge management. Furthermore, no W^2IO exists for China.

To fill this gap, we developed a new W^2IO model with high sludge and treatment resolution and implemented it for a Chinese city, Xiamen, resulting in the first W^2IO for a Chinese city capable of tracing the product origins of wastewater and

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sludge. Besides the consumption-based wastewater footprint of a product (W^2F), we developed the concept of consumption-based sludge footprint (SF) of a product, which refers to the amount of raw sludge produced by wastewater treatment processes (WWTPs) while treating the wastewater that originates from that product. In other words, it refers to the amount of sludge produced by WWTPs in treating all of the wastewater that was discharged in the entire supply chain of goods and services that resulted in that product.

A major source of wastewater and sludge is the toilet discharge of humane excreta, the origin of which is traced to food consumption, or to the postconsumption phase of food. In spite of the importance of this phase in the environmental impact of food,[29,30] little attention has been paid to it.[30−32] Inspired by these studies, attempts have been made to extend the W^2F and SF to accommodate the postconsumption phase of food, i.e., excretion.

The paper is organized as follows. After a brief explanation of the W^2IO framework, the next section deals with the data and methods. Section 3 is devoted to the results of W^2F and SF applied to the W^2IO table. Scenario analysis was conducted to assess the impacts on W^2F and SF of potential changes in industrial structure and diet. The paper closes with discussions on the policy implications, limitations, and directions for future research.

2. METHODS AND DATA SOURCES

2.1. W^2IO Table. The accounting framework of our model, the W^2IO table, is schematically given in Table 1. It is a combination of a standard IO table measured in monetary units, with the flow of goods and services in the rows referring to production and the flow of waste in physical units in the rows referring to waste (further detailed in Table S1 in the Supporting Information). The depiction of wastewater and sludge treatment processes with a high resolution is another distinguishing feature of the W^2IO table.

Table 1. Framework of a W^2IO Table with *n* Production Sectors, *m* Waste Items, and *k* Treatment Sectors[a]

	production (*n*)	treatment (*k*)	final demand	output/total
production (*n*)	X_P	X_T	y_P	x_P
waste (*m*)	W_P	W_T	y_W	x_W
treatment (*k*)	SW_P	SW_T	Sy_W	$x_T = Sx_W$

[a]While waste includes wastewater, sludge, and ash, wastewater discharge is the only nonzero element in the direct discharge from final demand, y_W.

Based on the Xiamen IO table for the year 2012, a W^2IO table for a Chinese city was developed for the first time. It involves 139 economic sectors (n = 139), seven wastewater treatment sectors (k = 7), and six waste/wastewater items (m = 5) (see Table S2 for the detailed classification of products, waste, and treatment sectors). As treatment is aggregated with water supply in the original Xiamen IO table,[33] they were disaggregated using the data on investment expenditure and operating costs of WWTPs.[34] The data on wastewater treatment capacity, sludge generation, and COD were obtained from the Xiamen Municipal Construction Group and CCNPS[35] (see Section 2.2 of the Supporting Information for further details of data development). Because agriculture is a nonpoint source of pollution, and 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. For expositional purposes, Table S4 shows a concise version of the W^2IO table with the original 139 economic sectors consolidated into three sectors.

2.2. Wastewater and Sludge Footprints of Products. Following Nakamura and Kondo[19,20] and Lin,[18] the wastewater footprints of products (W^2F_p) and of the discharge of wastewater from the final demand sectors (W^2F_W) are given by

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

where the *A*s and *G*s refer to technology matrices obtained as $A_P = X_P\hat{x}_P^{-1}$, $A_T = X_T\hat{x}_T^{-1}$, $G_P = W_P\hat{w}_P^{-1}$, and $G_T = W_T\hat{w}_T^{-1}$ (see Table 1 for the notations, and Section 2.1 of the Supporting Information for details of the derivation of this equation) and $\wedge$ refers to the diagonal operator. Let the first-row element of W^2F's be wastewater. The *i*th element of the first row of W^2F_P then gives the wastewater footprint of the final consumption of product *i*. The corresponding element of W^2F_w gives the wastewater footprint of the wastewater directly discharged by the final demand sector, that is, the amount of wastewater induced in treating the wastewater discharged by private households. The W^2Fs correspond to scopes 1−3 of carbon footprint.

The wastewater is transformed, among others, into sludge and refined water after undergoing treatment in WWTPs. Extending the concept of wastewater footprints, we introduce sludge footprints, SF_p, to trace the final demand origin of sludge. Wastewater from different production sectors may have different chemical (organic) compositions, resulting in different amounts of sludge per wastewater. In calculating SF_p, it is necessary to consider these sector-specific features of wastewater. This distinguishes SF_p from W^2F_P. We chose to use COD as a proxy for the organic content of wastewater.[31,36] In particular, the row elements of the original W^2IO flow referring to wastewater were replaced with COD elements (the amounts of wastewater submitted to A2O, OD, and BF were replaced with the corresponding amounts of COD), resulting in a new set of G_P, G_T, A_T, and y_w. Denoting these newly obtained matrices and variables by attaching "*," SF_p and SF_w are given by

$$(SF_p\ SF_w) = (G_P^*\ G_T^*)\begin{pmatrix} I - A_P & -A_T^* \\ -SG_P^* & I - SG_T^* \end{pmatrix}^{-1}\begin{pmatrix} \widehat{y_P} & 0 \\ 0 & \widehat{S\,y_W^*} \end{pmatrix} \quad (2)$$

where SF_w refers to the sludge footprint of the direct discharge from the final demand sector.

The W^2IO table compiled in this study is a single-region table focusing on the activities in Xiamen with imports exogenously given. Accordingly, eqs 1 and 2 were adjusted to exclude the impacts of imports (see equation (S10) in the Supporting Information for details). The system boundary is set to the activities in Xiamen, and only the local W^2F and SF will be considered. Still, issues of transboundary trade will be briefly addressed.

2.3. Postconsumption Footprint. Inspired by Sonesson et al.[31] and Muñoz et al.,[32] attempts were made to extend the W^2F and SF to include the postconsumption phases as well. To

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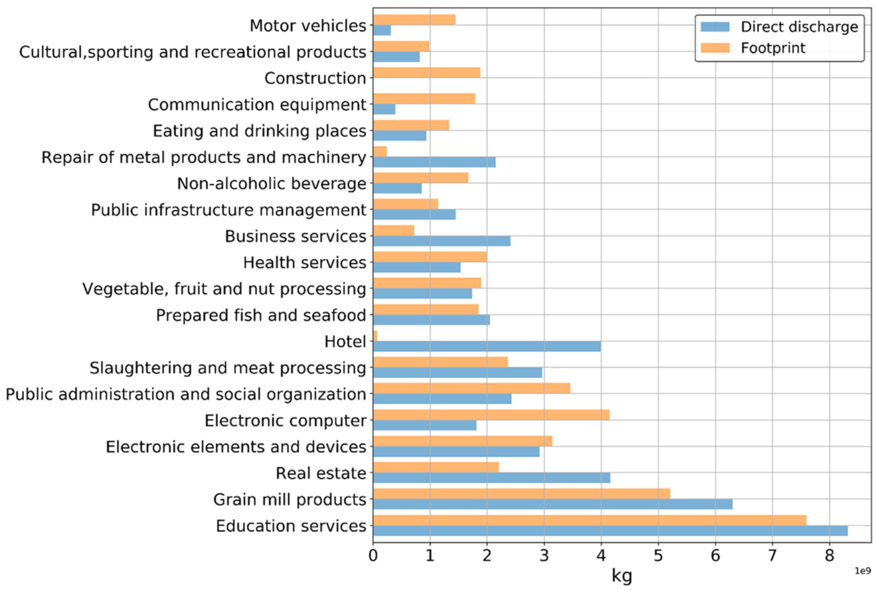

Figure 1. W^2F and direct wastewater discharge by products.

be more specific, this extension corresponds to allocating W^2F_W in eq 1 and SF_w in eq 2 to its product (food) origins.

For food item i, the consumption of the item in a physical unit and the discharge of toilet water associated with its excretion are denoted by y_i and θ_i, respectively. The postconsumption wastewater footprint of product i ($W^2F_{post\text{-}i}$) is then given by

$$W^2F_{post-i} = \theta_i \times y_i \quad (3)$$

The data on θ_i and y_i were obtained from Muñoz et al.[32] and Statistical Yearbook,[37] respectively (Table S6). As the information on θ_i for China was not available, we used the data from the EU[32] (see S15 in the Supporting Information for further details).

Further, we consider postconsumption SF; following our derivation of SF_p, we use COD as a proxy for the organic content of wastewater. We further assume that the carbon content of a food item determines the COD of wastewater discharged with its excretion. Denoting the carbon content of food i as C_i (Table S6), the ratio of the total carbon in food to the COD of toilet origin as C_0, and the ratio of the raw sludge to the total COD received by the WWTP j as α_j, the postconsumption SF (SF_{post}) is given by

$$SF_{post-i} = (\sum_{j=1}^{k} \alpha_j s_{j,ww}) \times C_0 \times C_i \times y_i \quad (4)$$

The total COD from the household sector needs to be allocated to bathing/washing, toilet use, kitchen, and others. Among these sources, toilet is most closely related to the postconsumption stage of food.[29,31] Due to the paucity of data relevant to China, we used the EU data of COD concentration (1.447 kg/m^3) of wastewater from toilets as provided by Henze.[36] We used the data on Singapore (16% for toilet) taken from JWRC[38] for the division of household wastewater discharge into different sources. This choice was made considering the similarity between Xiamen and Singapore in terms of the climatic zone and diet patterns.

2.4. Scenario Analysis and Sensitivity Analysis. As an application of W^2F and SF, two scenario analyses were considered, one involving changes in industrial structure and the other involving changes in diet patterns. To examine the robustness of the results, we conducted a sensitivity analysis for key parameters based on the sensitivity elasticity of parameters,[39,40] which indicated the ratio by which a change in "key parameters" changed the results for W^2F and SF.

3. RESULTS

3.1. Wastewater Footprints. Figure 1 shows the direct wastewater discharge and W^2F obtained by eq 1 for the top 20 sectors that occupied 69.2% of the total direct wastewater discharge. Education services and grain mill products were the largest contributors to wastewater discharge in terms of both direct discharge and W^2F. There are 1171 schools in Xiamen, with students and teachers making up 24% of the total population in the year 2012. All of the university students and a major fraction of middle and high school students live in dormitories, where meals are provided. This results in educational facilities consuming large quantities of water and discharging large quantities of wastewater, indicating potentials in both water-saving and wastewater recycling by decentralized treatment. Food-related sectors are also characterized by large discharges in terms of both direct discharge and W^2F.

However, there are products for which the contribution of direct discharge and footprints are markedly different. By construction, the sum of wastewater/sludge footprint for all products is equal to the sum of direct discharge from all production sectors (see Supporting Information). At the level of individual production sectors, however, some sectors may have a higher footprint than direct emissions, while the opposite may apply to others, depending on its position in the whole supply chain. For example, the "Hotel" sector is a major contributor in terms of direct discharge but is a minor one in terms of W^2F_P, indicating that the demand for the Hotel sector is mostly induced by the demand for other products. An IO calculation reveals that 50% of the demand for the Hotel sector is attributed to "Public administration and social organization", "Building materials", "General equipment", and "Construction". This implies that the major driver of the demand for the Hotel sector and hence its large wastewater discharge is not

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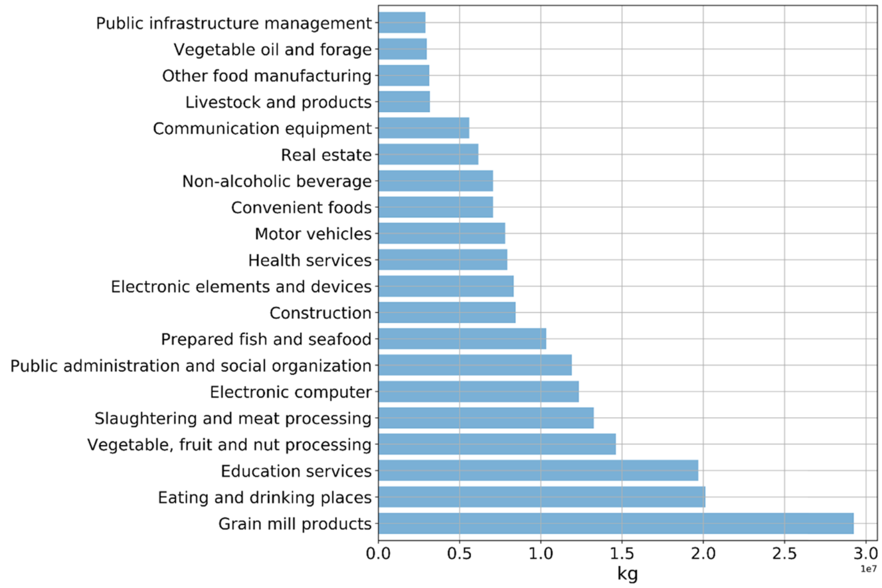

Figure 2. Raw sludge footprint of the top 20 products.

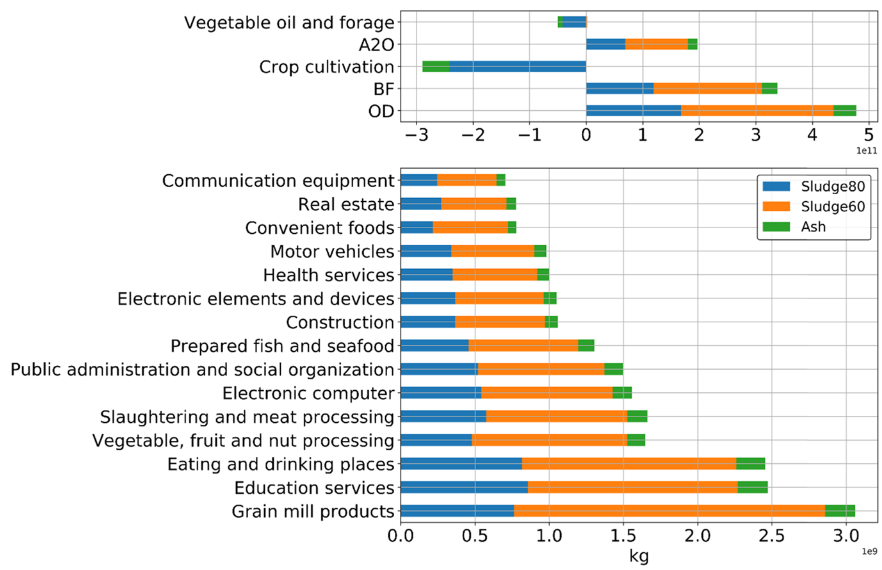

Figure 3. Dewatered sludge and ash footprints of products.

tourists visiting Xiamen for sight-seeing but workers in the construction, electronics industries, and the public sector. With the expected growth of these industries, the amount of wastewater from the Hotel sector would also increase. A similar result applies to "Business services" and "Repair of metal products and machinery," although to a lesser extent.

In contrast to the case of Hotel, W^2F_P far exceeds direct discharges for "Electronic computer," "Communication equipment," Construction, and "Motor vehicles". While the contribution from these sectors may appear minor in terms of direct discharges, their footprints are as large as those of many food-related sectors such as "Prepared fish and seafood" and "Vegetable, fruit and nut processing." Electronics manufacturing is a fast-growing industry in Xiamen, producing a quarter of its GDP. An IO calculation reveals that the major driver of the demand for the electronic computer sector is "Electronic elements, communication and other special equipment" and "Battery". The large wastewater footprints of these industries imply growing amounts of wastewater discharge associated with their growth.

The above results indicate the presence of sizable differences in the pattern of direct discharge and W^2F of products. In fact, with $r = 0.77$ for the largest 40 products that make up 93% of direct wastewater discharge, the overall correlation between them was found to be poor (Figure S1).

3.2. Sludge Footprints. Figure 2 shows the raw sludge footprints of the final demand for products, SF_p (eq 2), for the top 20 products make up around 80% of the total raw sludge originating from production sectors. A comparison with W^2F_P in Figure 1 shows a noticeable difference in the footprint ranking of sectors. Eight out of the 20 sectors with the highest SF_p refer to food-related products, compared to five for W^2F_P, and food-related sectors contribute to about 48% of the total SF_p. However, manufacturing sectors such as electronics, cars, and construction are also characterized by a sizable SF_p. In addition to the larger volumes of sludge attributed to these

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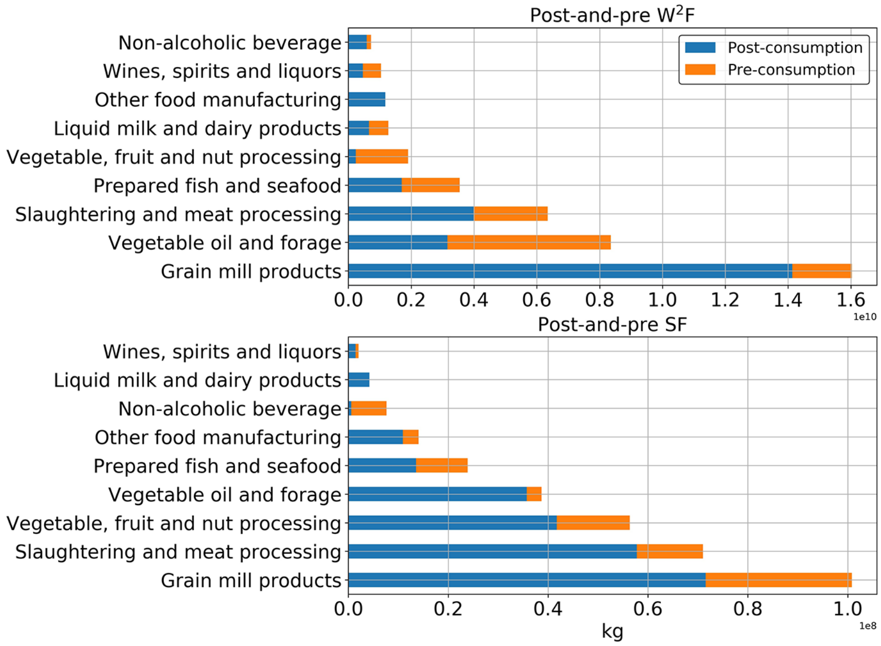

Figure 4. Pre- and post-W^2F and SF of food consumption.

sectors, their expected growth would also lead to a qualitative change in the composition of sludge that used to be dominated by food-based organic waste.

3.3. Recycling and Disposal of Dewatered Sludge. After being dewatered, sludge is either composted for recycling as fertilizer or disposed to a landfill (directly or after incineration). Figure 3 shows the SF_p and SF_w in terms of dewatered sludge and ash. The dominant contribution of the latter (A2O, BF, and OD) reflects the dominant shares of households in total wastewater discharges (see Table S4). The household sector accounts for around 70% of sludge 60. While the sludge of this category is landfilled, more than 60% of sludge 80 is recycled through composting in the agricultural and food sectors, with the rest being incinerated. "Crop cultivation" through its use as compost contributed to a significant reduction (2.91×10^7 kg) in the amount of sludge 80 that otherwise would have been incinerated and generated around 5090 kg of incineration ash. The negative contribution of sludge generation due to "Vegetable oil" can be traced to its sizable input from crop cultivation, although to a much smaller extent.

3.4. Postconsumption Footprints. Figure 4 (the upper panel) shows the postconsumption W^2Fs of nine food items that appear in the W^2IO table together with the W^2Fs referring to the preconsumption phase. The sum of the postconsumption W^2Fs amounted to 2.6×10^{10} kg, i.e., 18% of the total discharge from the household sector. Except for "Grain mill products," "Prepared fish and seafood," "Nonalcoholic beverage," and "Vegetable oil and forage," postconsumption W^2F exceeds the preconsumption W^2F. Due to the absence of the "Liquid milk and dairy products" sector in Xiamen, its preconsumption W^2F is zero. Out of the nine food items considered, "Vegetable, fruit and nut processing" has the largest total W^2F involving both pre- and postconsumption phases due to its highest consumption by mass. The fact that around 50% of it is imported from other cities/provinces explains the relatively smaller amount of its pre-W^2F. The postconsumption W^2F accounts for 65% of the total (pre- and postconsumption) W^2F in Xiamen, out of which meat, seafood, and milk and dairy consumption make up around 16.3%. While the consumption of "Grain mill products" and "Slaughtering and meat processing" is almost equal in terms of mass (Table S6), the postconsumption W^2F of the latter is larger than that of the former due to its greater requirement of toilet water for excretion (Table S6). The continuing shift in the pattern of diet away from grain to more of meat, seafood, and dairy products caused by increasing income levels is likely to increase W^2F.

Figure 4 (the lower panel) shows the food SF in both pre- and postconsumption stages in terms of raw sludge. We notice some remarkable differences in the postconsumption W^2F in the upper panel. First, with the single exception of "Non-alcoholic beverage," the postconsumption SF exceeds the preconsumption SF for all studied food items. Second, the ranking of products also differs, with Grain mill products having the largest SF in terms of both pre-SF and post-SF, followed by "Slaughtering meat processing" and "Vegetable oil and forage". Similar to W^2F, the ongoing shift in the pattern of Chinese diets is also likely to increase the volume of raw sludge in the future.

The significance of the postconsumption phase in the W^2F and SF of food indicates the importance of considering human digestion and excretion in the LCA of food products, confirming the findings of Sonesson et al.[31] and Munoz et al.[30]

3.5. Scenario Analysis. Two scenarios were considered to assess the effects of possible changes in industrial structure and diet patterns (for details of the setup and results, see the Supporting Information). The first (scenario 1) is based on the rate of industrial growth anticipated in the 13th Five-Year Plan (2016−2020) for economic and social development in Xiamen city, according to which a 2.3-fold increase in the final demand for the products of 15 manufacturing sectors is expected. The results (Table 2) indicate that while an increase in direct wastewater discharge will be 7%, the impact will be about twice the direct discharge (an increase of 13%), indicating the importance of considering footprints in industrial planning.

Table 2. Effects of Industrial Growth and Changes in Diet Patterns on Wastewater and Raw Sludge[a]

	scenario 1 industrial growth		scenario 2 change in diet	
	increase	rate (%)	increase	rate (%)
direct wastewater discharge	1383	7	4919	2
W^2F	2647	13	6338	3
SF	77 192	7	33 429	3

[a]Units: Increase in 10^7 kg for wastewater and 10^3 kg for sludge. Rate of change relative to the 2012 value. (1) The final demand for products of sectors 75, 76, and 78–90 (electronics and cars) increased by 2.3-fold. (2) The consumption of the second to the six food items in Table S3 increased by a factor of 1.5 to 11 to match the Spanish level in Table S4.

The second scenario (scenario 2) refers to a possible shift in diet from the traditional Chinese one mostly based on staples toward a European one involving larger amounts of animal-sourced foods. The results indicate an increase in direct discharge of 2 and 3% in both W^2F and sludge generation, respectively (Table 2).

3.6. Sensitivity Analysis. We first assessed the sensitivity of the preconsumption W^2F and SF to a set of 20 underlying coefficients referring to input and waste generation. Most of the sensitivity elasticities to these coefficients were small (Table S7), except for the sludge generation coefficients. The fact that those coefficients are obtained from the annual WWTP operation in Xiamen and are highly reliable implies the reliability of our results.

We next assessed the sensitivity of the postconsumption W^2F and SF to the parameters θ_i and α_j. The elasticities of these footprints to θ_i were rather small ranging between 0.01 and 0.54, with the largest value for "Vegetable, fruit and nut processing" (Table S8). This product accounts for the largest part (53%) of total food consumption and has the highest influence on post-SF. The post-SF was found to be sensitive to α_j of the OD treatment due to its largest treatment capacity. The fact that this parameter was obtained from annual WWTP operation data and is of high reliability implies the reliability of our postconsumption SF results.

In calculating the postconsumption impacts, we used the toilet share of wastewater for Singapore, 0.16. The fact that this value is small compared to those in London, Lyon, and Tokyo (around 0.22)[38] would imply that the above finding of the postconsumption SF exceeding the preconsumption SF is a robust one (because a higher value implies a larger amount of postconsumption sludge).

3.7. Transboundary Impacts. Since the final demand y_P includes export to other regions and countries, a portion of the above footprints is attributed to the demand originating from outside Xiamen. It turns out that export has the largest contribution to W^2F (42%), followed by urban household consumption (33%) (Figure S2). Export embodies the largest fraction of wastewater generated in Xiamen. Following the practice of carbon footprinting,[41] the amounts of wastewater and sludge embodied in international trade were calculated. It turned out that Xiamen is a net exporter of wastewater and sludge (Table S9). It is not the case that Xiamen is keeping its water resources clean at the expense of other regions of China.

4. DISCUSSION

4.1. Policy Implications. The results highlighted remarkable differences between W^2Fs and direct discharges. Focusing only on direct discharges can be misleading because its footprints can be much larger. Direct wastewater discharge is being used as a key indicator of environmental pollution in China.[42] Some industrial parks do not permit the entry of industries with high wastewater discharges. W^2F provides new insight into this landscape by considering the final demand origins of wastewater and the interdependence of production and treatment sectors in the economy. As demonstrated in the above scenario analysis, W^2F enables the assessment of the impacts on wastewater discharge and sludge generation with changes in the final demand for products brought about by industrial growth or consumer preferences.

The W^2IO allows for the assessment of an industry's contribution to the circular economy. The economy-wide fate of dewatered SF (Figure 3) reveals that sludge can re-enter the economic system through compost and lead to a significant reduction in sludge for treatment and disposal. Future sludge treatment is expected to explore further sustainable options including other sludge-to-resource technologies. Recycling of incineration ash as construction materials after pretreatment and metal recovery could be a promising option, conditional on a comprehensive evaluation of environmental risk.[43,44] The application of sludge to land could be an important future development. An emerging way of carbon capture and utilization in WWTPs is the pyrolysis of sludge to produce biochar, which can be used by agriculture, among others, for soil amendment.[45]

4.2. Limitations and Future Research. To the best of our knowledge, this study is the first to develop a W^2IO model for China and consider consumption-based wastewater and sludge footprint of products. Still, it has several limitations, some of the major ones are as follows. This study used COD only to represent the chemical characteristics of wastewater. The increasing consumption of meat and dairy products implies a need to look more closely at the N content as well. In calculating the postconsumption footprints, a simple relationship was assumed between the COD of household wastewater and sludge and the carbon content of individual food items. In addition to extending the coverage of elements, more elaborate considerations of the underlying chemistry between the inputs and the wastewater and sludge resulting from their eventual discharge would be desirable. This applies not only to the wastewater discharged by households but also to that discharged by industries.

Another important direction for future research is to extend the current single-region framework to a multiregional one based on a multiregional W^2IO.[25,27,46] This would help assess the transboundary impacts of urban development, quantify the spatial distribution of impacts along the regional supply chains, and provide quantitative information for discussion about regional responsibility sharing.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c01517.

The details in materials and W^2IO methods (Tables S1–S6); supplementary results (Tables S7–S9, Figures S1–S2) (PDF)

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Notes

The authors declare no competing financial interest.

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