Understanding the pathway of phosphorus metabolism in urban household consumption system: a case study of Dar es Salaam, Tanzania

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Abstract: Phosphorus discharge in urban household consumption system has an important impact on the urban ecological environment, especially the surface water environment. In this study, a framework and its accounting model of phosphorus flow analysis in urban household consumption system by means of SFA (substance flow analysis) was constructed. Based on the accounting model, the flow of phosphorus in the urban household consumption system of Dar es Salaam was described quantitatively, and the results demonstrated: (1) the total phosphorus input, stock and output of urban household consumption system in Dar es Salaam were 4874t of P, 59t of P and 4815t of P, respectively. In terms of system input of phosphorus, residents' food consumption had a decisive impact on the system's phosphorus input (4765t of P, 97.76%), while the contribution of detergent to the phosphorus input of the system was small. In terms of system phosphorus output, human feces and urine phosphorus output accounted for the majority of the total system phosphorus output (2313t of P, 48.04%). The total phosphorus output of domestic garbage, wastewater and food processing loss were 1464t of P (30.41%), 561t of P (11.65%), 477t of P (9.90%), respectively. (2) There were 2314t of P discharged into surface water through human feces and urine and domestic wastewater, which had a negative impact on the prevention and control of surface water pollution. 34t of P came from scattered garbage storage and 315t of P came from centralized garbage storage due to limited treatment capacity of waste treatment plant. Centralized storage and decentralized storage increased the risk of further phosphate loss. (3) Accelerated urbanization, rapid economic development and low sewage treatment capacity would cause more phosphorus loss, and Dar es Salaam faced great challenges in P discharge reduction and pollution control. Finally, we proposed policy recommendations for P discharge reduction including the guidance to the reasonable dietary structure with low phosphorus, the promotion of cleaning products with less phosphorus and no phosphorus, and the construction of garbage treatment and sewage treatment infrastructure.

Key words: Dar es Salaam; Urban household consumption system; Phosphorus metabolism process; Substance flow analysis; Environmental management

1. Introduction

Phosphorus is an indispensable nutrient element for living systems and is widely used in various aspects of human social and economic activities (Liu et al., 2016; Cordell, 2009; Wu et al., 2015). About 90 % of the phosphorus extracted from nature is used in products such as fertilizers, feed, food additives and detergents to satisfy the needs of modern urban household consumption systems (Li et al., 2010; Matsubae-Yokoyama, 2009). Phosphorus is a limited and non-renewable resource extracted from rocks. Although the life cycle of global phosphorus reserves is uncertain, studies have shown that, with current technical conditions and mining rates, the peak of global phosphate rock production will appear in 2030, and the average grade will decline significantly, leading to the rising cost of extraction (Stewart et al., 2005; IFA,2006). What's worse, the global phosphorus mine is estimated to be exhausted in the next 50-400 years (Cordell and Write,2014;Reijnders,2014;Scholz et al.,2013; Chowdhury et al.,2016; Firmansyah et al.,2017). Rising global demand for food, changing diets and increased use of detergents are the main reasons for the rise of phosphorus. Production of farm products, meat, dairy products and detergents requires more phosphorus input than ever before (Suh and Yee, 2011). Meanwhile, the unreasonable discharge of phosphorus is the main cause of water eutrophication and other water pollution problems, and has attracted worldwide attention (Chen, 2008).

Cities are highly dependent on external materials. The high input of phosphorus makes cities a hotspot for research. Meanwhile, phosphorus discharge causes environmental problems such as urban water environment deterioration and water crisis. While residents' consumption is the driving force that causes phosphorus to flow in cities and the consumption structure determines the type, structure, scale and direction of agricultural planting, livestock and poultry breeding and chemical production to a certain extent. With the acceleration of urbanization and the high quality development of cities, it is urgent to do research on phosphorus consumption of urban residents. Therefore, quantifying P flows in residents' consumption is vital for the selection of successful nutrient management strategies and urban sustainability. Substance flow analysis (SFA) is an effective method to connect material utilization with its environmental impacts, which aims at reducing or substituting harmful environmental fluxes by tracing sources, discovering future problems and forming a basis for regulation (Eriksson et al., 2008). It can be used to analyze the amount and intensity of P use and thus develop environmental management strategies (Guo and Song, 2008).

Cities are the most concentrated geographical units of human social and economic activities (Ren et al., 2019). With the advancement of urbanization, the traditional nutrition relationship between urban population and land has become increasingly loose due to the distance between urban and rural areas (Driver, 1998). For example, in the past, nutrients that humans absorbed from food were metabolized by the body and excreted as feces, usually in the form of organic nutrients into a closed or quasi-closed system for recycling. But these days, sewers and flush toilets are often built to remove the city's growing supply of feces and sewage. Obviously, this treatment greatly increases the load of phosphorus nutrients in the water without considering whether the nutrients are fully recycled. A series of environmental problems in cities are determined by the metabolic nature of cities. During the process of urban metabolism, a large amount of materials and energy are imported, most of which are stored in the form of buildings and urban infrastructure, while food and other materials are consumed. In the process of consumption, the waste generated is recycled or moved, and the final waste is discharged into the atmosphere, land and water environment in different forms, resulting in the decline of urban environmental quality (Kennedy et al., 2007). Urban development has seriously disturbed the natural cycle of phosphorus and damaged the ecological environment, which has become P "hotspots". (Cohen, 2006; Buathong, 2013; Zhang et al., 2017; Hou et al., 2018). Currently, Phoenix in the United States, Paris in France, Sydney in Australia, Gothenburg in Sweden, Haiphong in Vietnam, Beijing, Shanghai and Chongqing in China are among the cities carrying out studies on phosphorus metabolism(Metson et al.,2012; Verger et al.,2018;Tangsubkulet al.2005; Kalmykova et al.,2012; Aramaki et al.,2010;Qiao et al.,2018). As one of the important components of urban metabolism, household consumption increases rapidly with the increased urbanization rate. Phosphorus is an essential element in human life, which flows and transforms with the process of household metabolism. Its flow pattern and flow rate are closely related to environmental quality. Studies showed that the impact of urban household consumption system on the eutrophication of regional surface water could not be ignored, especially in the absence of an effective waste collection and treatment system (Li et al., 2010; Yuan et al., 2011). At present, the urban development in Africa continent is in the early stage of urbanization process, and there is a lack of phosphorus research on cities and their subsystems.

SFA is a quantitative analysis tool to understand and characterize the flow of phosphorus in a specific system (Cooper, 2013; Grames et al., 2019). SFA has been widely used in the global (Liu,2006;Nesme et al.,2018； Grames et al.,2019; Koppelaar et al.,2013), national (Antikainen.,2004; Seyhan.,2009; Smit.,2010; Ghani.,2011; Cooper.,2013) and urban (Neset.,2008; Metson.,2015a) regional phosphorus flow analysis at different geographical scales. These studies explored the process of phosphorus metabolism from a systematic perspective and provided valuable information for phosphorus management. However, the process of phosphorus metabolism in household consumption as a system has not been clearly described (Bai et al., 2016), and there are much space for in depth study.

Africa is the fastest urbanized region in the world, and its urban population will triple to 1.23 billion between 2010 and 2050 (UN-Habitat, 2010). Rapid urbanization is exacerbating water pollution and drinking water safety problems in African countries. Most countries in sub-Saharan

Africa did not meet the UN's MDG (millennium development goals), with only about 60% of the population having access to safe drinking water. And Tanzania did not achieve the MDG targets in 2015 (Mapunda, Chen & Yu, 2018). The water quality survey report of major cities in Tanzania showed that the water quality of urban rivers was generally deviated in the whole or part of the river sections, and the water environment was greatly affected by urban residential areas (NIGLAS & TAFIRI, 2017). It is necessary to carry out research on consumption metabolism of urban residents in order to formulate water environment management policies. Therefore, taking Dar es Salaam as an example, we used SFA to construct the framework and its accounting model of phosphorus flow analysis in urban household consumption system, clarified the basic pattern of phosphorus flow in the process of urban household consumption, analyzed the metabolic law and structural characteristics of phosphorus in the system, and calculated the phosphorus discharge of the household consumption system, especially the phosphorus discharged into the surface water. Thus, it can provide important support for the optimal control of phosphorus in urban household consumption system and the control of pollution of urban surface water.

There are two innovative points in this paper. First, it clearly describes the process of phosphorus metabolism in urban household consumption system. Second, it fills the gap of phosphorus flow analysis in African urban areas.

2. Materials and methodology

2.1. Study area

Dar es Salaam is located along the west coast of the Indian Ocean in eastern Tanzania, between 6°33 '50 "~7°10' 48" S, 33°33 '19 "~39°33' 7" E(Fig.1). It is consists of 5 inner districts with a total area of 1628 km^2, of which 235 km^2 (14.4%) is covered by water bodies, mainly in the

Indian Ocean. The land area is 1393 km^2, which is accounting for 0.16% of the total land area of Tanzania. There are many rivers in Dar es Salaam, and the seasonal variation of river flow is very significant under the influence of tropical climate. The urban population of Dar es Salaam was 5.78 million in 2017, accounting for about 10% of the total population of the country. Dar es Salaam was the national political, economic, and cultural center and transportation hub of Tanzania. Since the beginning of the 21st century, Dar es Salaam's GDP growth rate has remained above 10%, accounting for over 15% of the country's total GDP.

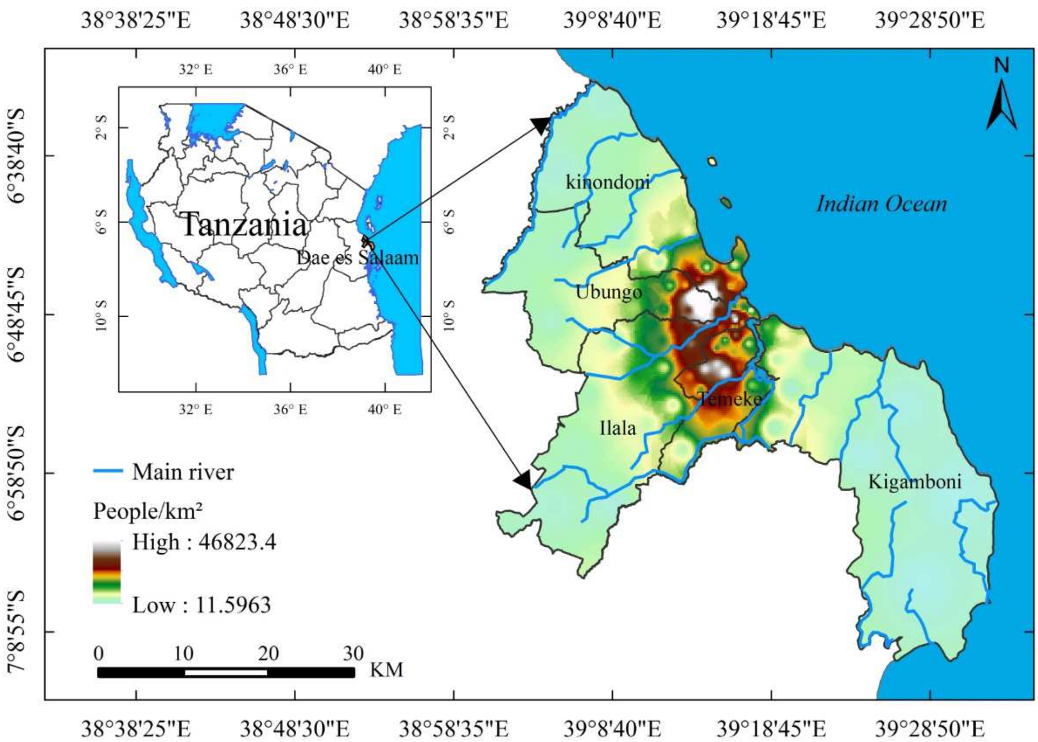

Fig.1 Location of Dar es Salaam

2.2. Urban household consumption system phosphorus flow analysis framework

The method used in this paper is SFA. Its equation can be described as "input = output + stock". It is used to track the magnitude and location of substances loss and stock changes in the system (Bringezu et al., 2009).This study established an analytical framework for phosphorus flow by means of SFA in urban household consumption system, quantitatively analyzed the main flow process of phosphorus in the process of household consumption, clarified the flow characteristics and flux of phosphorus in different links in the system, and the resulting main path affecting environmental quality. The basic process of phosphorus flow was: daily necessities (plant foods, animal foods, cleaning products and coal） input phosphorus into urban households. Residents maintained a normal life by consuming daily necessities. After household consumption, a small part of phosphorus was absorbed by the human body, and most of phosphorus was discharged through four ways: food processing loss, garbage, feces and urine, and wastewater. Feces, urine and wastewater were generally collected through the sewage pipe network into the sewage treatment plant, and the untreated were discharged into surface water. After the generation of household garbage, most of it was collected centrally for processing, and the rest was directly stored in the environment. The analysis framework of phosphorus flow in urban household consumption system was shown in the Fig. 2

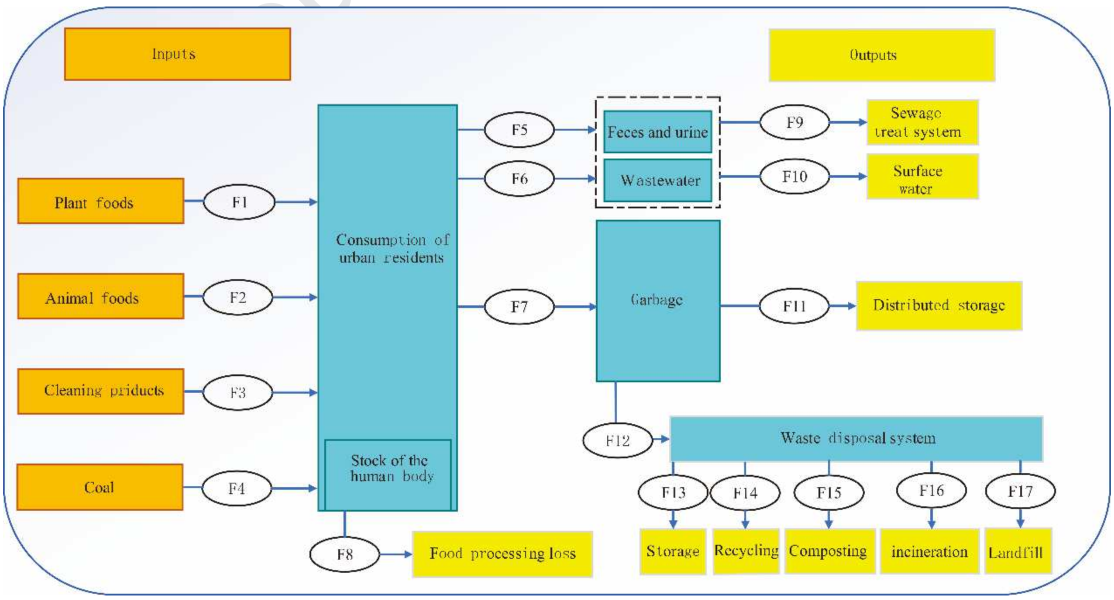

Fig. 2 Urban household consumption system phosphorus flow analysis framework

2.3. Data collection

The research data in this paper were mainly from statistical yearbook, household questionnaire survey, department interview, expert consultation, literature review, and field investigation.

The per capita consumption of household necessities in this study was mainly based on the urban household consumption questionnaire survey conducted by our research group in Dar es Salaam from June to July 2019. The contents of the questionnaire on urban household consumption included the basic situation of the family, the consumption of plant food, the consumption of animal food, the use of household detergent, the daily main energy consumption and the generation of kitchen waste. The sampling method adopted in this paper was stratified equal probability random sampling. With the assistance of researchers from Tanzania Fisheries Research Institute, we conducted a preliminary questionnaire survey in Kinyerezi (a ward in Ilala) on June 28, 2019.We recorded the problems in the preliminary draft of the questionnaire and further revised the questionnaire and determined the final survey questionnaire. The main feature of residential area in Dar es Salaam was that it is divided into formal residential area and informal residential area. In the study, we conducted household survey in three research sites (three wards in Dar es Salaam), which were divided into formal and informal residential areas. Sample ward, sample subward and sample household were determined according to the principle of stratified equal probability random sampling. Specifically, three of the 88 wards in Dar es Salaam were randomly selected, one informal subward and one formal subward were randomly selected from each ward, and 15 households were randomly selected from each subward. In July 2019, under the research permission of each district of Dar es Salaam, accompanied by researchers from the

Tanzania fisheries research institute, ward leaders, and subward leaders, we completed the urban household consumption questionnaire survey. We obtained 90 household questionnaires, of which 88 were valid, accounting for 97.78%. In this paper, SPSS were used to process and analyze the urban household consumption questionnaire, and the per capita consumption of household necessities was obtained (Table 1).

The population, wastewater collection, waste generation, collection and disposal in the study were determined mainly according to the environmental statistics yearbook of Tanzania 2017, household consumption questionnaire, department interview, literature review, and field investigation. (Table 2).

At the same time, according to the existing literature and field investigation, combined with the department interview and expert consultation results, we determined the phosphorus coefficient of main daily necessities of urban household. The phosphorus content coefficients of the substance and its source were summarized in Table 3.

Table 1 Consumption of main daily necessities based on urban household consumption questionnaire in Dar es Salaam

Type	Unit	Value
Maize	kg/cap/yr	40.51
Wheat	kg/cap/yr	18.99
Rice	kg/cap/yr	58.16
Sorghum	kg/cap/yr	2.99
Millet	kg/cap/yr	2.47
Banana	kg/cap/yr	16.78
Casssava	kg/cap/yr	19.33
Other grains	kg/cap/yr	0.27
Beans	kg/cap/yr	17.80
Peanut	kg/cap/yr	4.11
Tomatoes	kg/cap/yr	20.89
Cucumber	kg/cap/yr	6.17
Other vegetable	kg/cap/yr	38.36
Fruit	kg/cap/yr	71.94
Pork	kg/cap/yr	3.72

Beef	kg/cap/yr	15.23
Mutton	kg/cap/yr	1.60
Poultry	kg/cap/yr	16.10
Seafood	kg/cap/yr	19.26
Dairy products	L/cap/yr	19.63
Egg products	kg/cap/yr	3.84
Washing powder	kg/cap/yr	7.33
Laundry soap	kg/cap/yr	4.56
Laundry liquid	L/cap/yr	1.18
Hand sanitizer	L/cap/yr	0.72
Dishwashing liquid	L/cap/yr	0.48
Toilet liquid	L/cap/yr	3.14

Table 2 Household waste and wastewater treatment in Dar es Salaam

Category	Unit	Value	Source
Population	People	5781557	NBS,2018
Kitchen waste generation	kg/cap/yr	121.74	Household questionnaire survey
Kitchen waste dry matter content	%	40.00	Eggleston et al., 2006
Kitchen waste phosphorus content	%	0.52	Nie, 2000; Zhang et al., 2007
Waste collection rate from households	%	97.70	NBS,2018
Ratio of household waste recycling to total household waste	%	1.88	NBS,2015,2018;Interview with waste treatment enterprise
Ratio of household waste composting to total household waste	%	8.16	NBS,2015,2018;Interview with waste treatment enterprise
Ratio of household waste incineration to total household waste	%	0.89	NBS,2015,2018;Interview with waste treatment enterprise
Ratio of household waste landfill to total household waste	%	65.24	NBS,2015,2018;Interview with waste treatment enterprise
Wastewate collection rate	%	19.50	NBS,2018

Table 3 Phosphorus content coefficients of main daily necessities of urban households

Type	Unit	Mean value	Distribution	Source
Maize	%	0.400	Uniform（0.26, 0.54）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016
Wheat	%	0.500	Uniform（0.33, 0.67）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016
Rice	%	0.400	Uniform（0.26, 0.54）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016
Sorghum	%	0.360	Uniform（0.24, 0.48）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016

Millet	%	0.280	Uniform（0.18, 0.38）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016
Other grains	%	0.300	Uniform（0.20, 0.40）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016
Cassava	%	0.055	Uniform（0.03, 0.08）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015
Bananas	%	0.025	Uniform（0.02, 0.03）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015
Beans	%	0.600	Uniform（0.39, 0.81）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016
Peanut	%	0.500	Uniform（0.33, 0.67）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016
Tomatoes	%	0.050	Uniform（0.01, 0.09）	Souchi, 2001; USDA, 2011; Stadlmayer et al. 2012; Lederer et al., 2015
Cucumber	%	0.015	/	Souchi, 2001
Other vegetable	%	0.040	Uniform（0.26, 0.54）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016
Fruit	%	0.020	/	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015
Pork	%	0.185	Uniform（0.17, 0.20）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015
Beef	%	0.168	Uniform（0.11, 0.226）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016
Mutton	%	0.173	Uniform（0.146, 0.20）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016
Poultry	%	0.180	Uniform（0.139, 0.22）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015; Liu et al., 2016
Seafood	%	0.230	Uniform（0.20, 0.26）	Smil, 2000;USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015
Dairy products	%	0.082	Uniform（0.073, 0.09）	Yang , 2005; USDA, 2011; Stadlmayer et al., 2012; Lederer et al., 2015
Egg products	%	0.186	Uniform（0.162, 0.21）	Yang , 2005; USDA, 2011; Stadlmayer et al. 2012; Lederer et al., 2015
Washing powder	%	0.100	/	Yan,2008
Soap	%	0.131	/	Yan,2008
WC-cleaner	%	0.100	/	Yan,2008
Hand sanitizer	%	0.100	/	Yan,2008
Laundry liquid	%	0.100	/	Yan,2008
Dishwashing liquid	%	0.100	/	Yan,2008

205

2. 4. Accounting approaches to P balance

2. 4.1. Inputs

According to the basic principle of material flow analysis, phosphorus input in urban household consumption system is a function of the consumption of all phosphorus containing substances in the process of household consumption, namely:

$$f_{input} = \sum_i x_i * \alpha_i \qquad (1)$$

Where f_{input} is the total phosphorus input per capita of urban household consumption system; i is the type of phosphorus-containing substances; x is the per capita consumption of phosphorus-containing substances; α_i is the P-containing coefficient of phosphorus-containing substances.

According to the previous description, the phosphorus input of urban household consumption system includes three categories: phosphorus-containing food input, phosphorus-containing chemical products (mainly detergents) input and coal input. Our household survey showed that wood, charcoal and canned liquefied petroleum gas were the main fuels for urban households in Dar es Salaam, while the coal was rarely used. Considering the actual consumption situation of urban households in Dar es Salaam, the input of phosphorus-containing food included 27 kinds of plant food such as rice, wheat and corn, and 8 kinds of animal food such as beef and mutton; Phosphorus-containing chemicals input included 6 kinds of washing products, such as laundry soap, laundry liquid and hand washing liquid.

2. 4.2. Phosphorus stock

The amount of phosphorus in the human body is very small and the total amount of phosphorus in the normal adult body is about 400-900g. According to the world health statistics

2018 released by the world health organization, the average life expectancy in Tanzania was 63.9 years. The average phosphorus content in human body was taken as the average value of the total phosphorus content range of normal adult body, i.e. 650g, and the average annual phosphorus accumulation of Tanzanian human body was 10.2g.

Based on the above analysis, we obtain the system stock accounting equation:

$$f_{stock}=\frac{650}{63.9*1000}=0.0102 \qquad (2)$$

Where, f_{stock} refers to the per capita stock of the system, i.e. the average annual accumulation of phosphorus by the human body，its unit is kg capita^{-1}.

2. 4.3. Outputs

According to the phosphorus flow analysis framework of urban household consumption system, the phosphorus flow output of urban household consumption system mainly includes the following ways: the output caused by food processing loss, the output in the form of human feces and urine, the output in the form of kitchen waste and the output in the form of wastewater.

Food processing loss: it refers to the loss of phosphorus caused by food processing in order to ensure the normal daily dietary needs of urban residents, including the loss of phosphorus in processing and the part that cannot be absorbed by human body. Generally in the cooking process, the denaturation and dewatering shrinkage of animal food occurs when it is heated, and phosphorus is spilled and lost along with the water inside the meat. The loss of phosphorus in animal food may be as high as 32%, while the loss of phosphorus in plant food is relatively small in the cooking process. In this study, it was considered that about 10% of phosphorus in food was lost and not ingested by human body after pre-processing, heat treatment, swelling and other processes (Lu, 2008). Thus, we obtained the calculation formula of phosphorus per capita food processing loss:

$$f_{loss}=0.1*f_{food} \qquad (3)$$

Where f_{loss} refers to phosphorus per capita food processing loss, f_{food} is the total food phosphorus input per capita.

Feces and urine. The human body ingests phosphorus through food and drink, and after metabolism, excretes it through the intestines and kidneys, mainly through the kidneys. The phosphorus excreted by the human body through the kidneys accounted for 70% of the total excreted amount, and the phosphorus excreted through the intestines with feces accounted for about 30% (Hu, 2000). In areas without sewage treatment facilities, human excreted feces and urine are generally discharged directly with sewage into local rivers and ditches, which has adverse effects on surface water environment. In urban areas with sewage treatment facilities, human excreted feces and urine together with domestic sewage go through sewage collection pipes to sewage treatment plants for treatment. Based on the above analysis, it is considered that the treatment rate of human feces and urine is the same as the treatment rate of domestic wastewater. Phosphorus content of human feces and urine in East Africa (Jonsson et al., 2004) is shown in the table 4.

Table 4 Phosphorus content of human feces and urine

Type	kg/year*capita
Feces	0.1
Urine	0.3

The calculation formula of phosphorus output per capita of urban residents in human feces and urine was as follows:

$$f_{human}=0.1+0.3=0.4 \qquad (4)$$

Kitchen waste. Kitchen waste refers to the waste generated in daily life and food processing activities of residents, including discarded unused vegetable leaves, leftovers, peel, eggshell, tea residue, bone, etc., which mainly comes from family kitchen. Phosphorus in household garbage is mainly found in kitchen waste (Zhang et al., 2007). The calculation formula of phosphorus content of kitchen waste per capita of urban residents was as follows:

$$f_{waste}=\alpha_{waste}*\mu*q \qquad (5)$$

Where, f_{waste} is the phosphorus output of per capita household waste of urban residents. α_{waste} is the phosphorus coefficient, μ is the dry matter content, and q is the per capita kitchen waste of urban residents.

Wastewater. All of the accounting processes based on SFA for P flows should obey the principle of mass balance. On the basis of determining the input, stock and other output items of phosphorus in urban household consumption system, the phosphorus content of wastewater was calculated by balancing the input and output of the system. The calculation formula of phosphorus content in per capita domestic wastewater discharge was as follows:

$$f_{wastewater}=f_{inputs}-f_{stock}-f_{loss}-f_{human}-f_{waste} \qquad (6)$$

3. Empirical results

3.1 General analysis of phosphorus flow

The total phosphorus flow analysis results of urban household consumption system in Dar es Salaam were shown in Fig. 3. In 2017, the total phosphorus input, stock and output of urban household consumption system in Dar es Salaam were 4874t of P, 59t of P and 4815t of P, respectively.

In terms of system input of phosphorus, plant food input was 4003t of P, accounting for 82.13% of the total phosphorus input, animal food input was 762t of P, and accounting for 15.63% of the total phosphorus input, and washing products input was 109t of P, accounting for 2.24% of the total phosphorus input. In urban household consumption system, residents' food consumption had a decisive impact on the system's phosphorus input (97.76%), while the contribution of detergent to the phosphorus input of the system was small.

In terms of system phosphorus output, human feces and urine phosphorus output of urban household consumption system in Dar es Salaam accounted for the majority of the total system phosphorus output in 2017 (2313t of P, 48.04%). Feces and urine were discharged together with domestic wastewater (561t of P, 11.65%). And with statistical data from department of statistics, it showed that wastewater treatment rate in Dar es Salaam was 19.5% (NBS, 2018). So only a small part (560t of P, 11.63%) went through the sewage collection pipe network into the sewage treatment plant for centralized treatment, and most of it was directly discharged into the surface water. The amount of phosphorus discharged into the surface water directly was about 2314t of P (48.06%), which had an adverse impact on the environmental quality of surface water. The total phosphorus output of domestic garbage was 1464t of P, accounting for 30.41% of the total phosphorus output. Most of it (1430t of P, 29.70%) entered the solid waste treatment system for further treatment after centralized collection, and about 34t of P (0.71%) was directly stacked in the environment. It should be pointed out that 477t of P (9.90%) was outputted in the food processing process, and this part of phosphorus was finally discharged into the atmosphere.

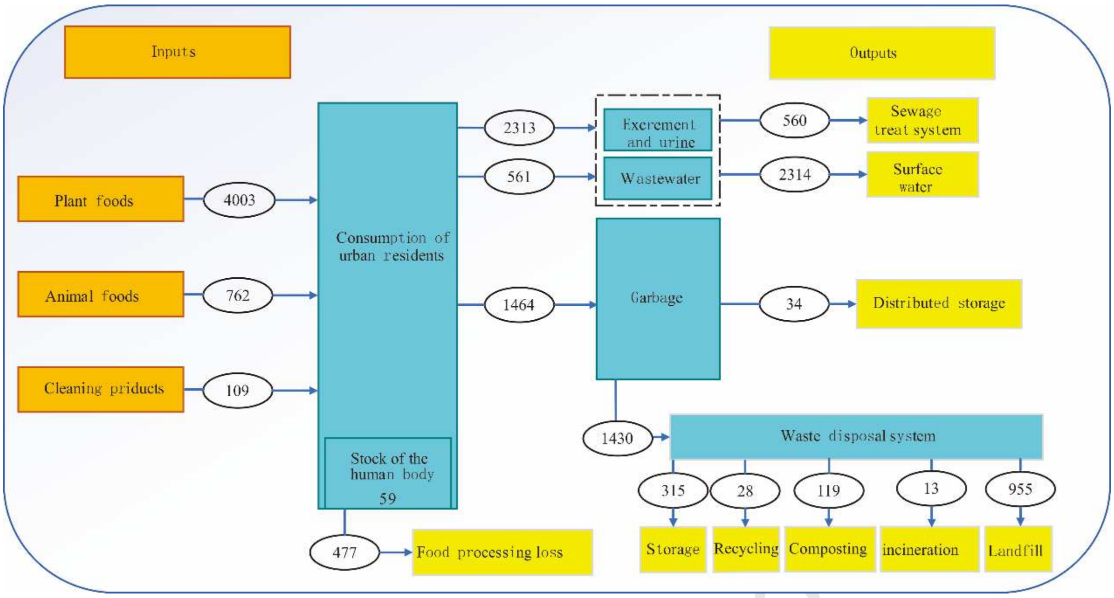

Fig3. Phosphorus flow in urban household consumption system in Dar es Salaam

3.2 Analysis of phosphorus flow characteristics

3.2.1 Analysis of phosphorus input characteristics

From the perspective of the consumption structure of plant food, rice was the main consumption of household plant food in Dar es Salaam (see Fig. 4), accounting for 33.60% of the total phosphorus input of plant food. The proportion of maize, beans and wheat was also higher in plant food, accounting for 23.40%, 15.43% and 13.71% of the total phosphorus input of plant food, respectively. Other important plant foods include vegetables, peanuts, fruits, sorghum, cassava, millet, and banana and so on. It should be noted that cassava was one of the main food crops in Tanzania, and bananas were the staple food of many families, so bananas were not included in the fruits. Cassava and banana were in the top five in the total consumption of plant food, but their phosphorus content was low (Table 2), so the input of phosphorus was less (Fig. 4).

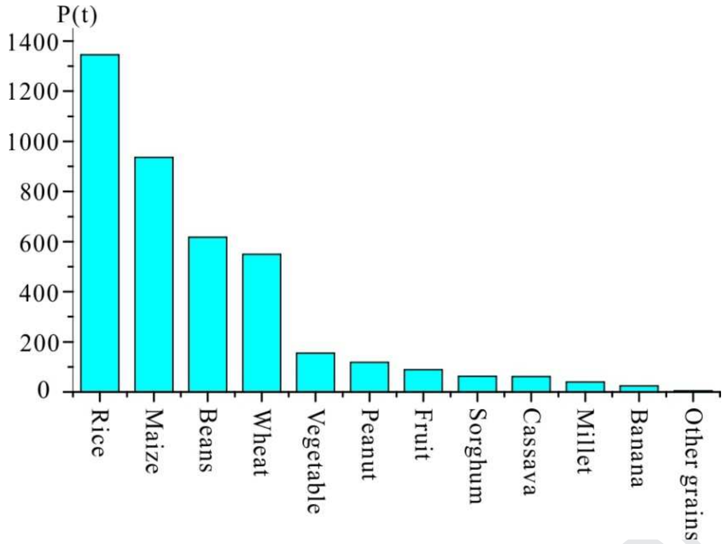

Fig. 4 Plant food consumption P input structure of urban household consumption system in Dar es Salaam

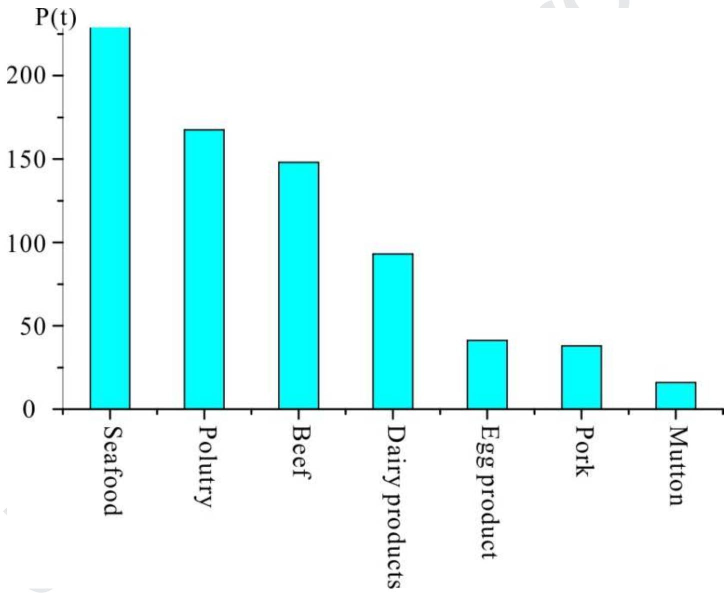

Fig. 5 Animal food consumption P input structure of household consumption system in Dar es Salaam

The consumption structure of animal food in urban household consumption system in Dar es Salaam was shown in Fig. 5. Because Dar es Salaam was a coastal city, among the animal food, seafood inputted the most phosphorus to the system, which was 256t, accounting for 33.60% of the total phosphorus input of animal food. The proportion of poultry, Beef and dairy products was also higher in animal food, accounting for 21.99%, 19.42% and 12.21% of the total phosphorus input in animal food, respectively. Chicken was the main poultry meat, accounting for 91.53% of the total poultry meat. Other important animal phosphorus input foods included egg products, pork, mutton and so on.

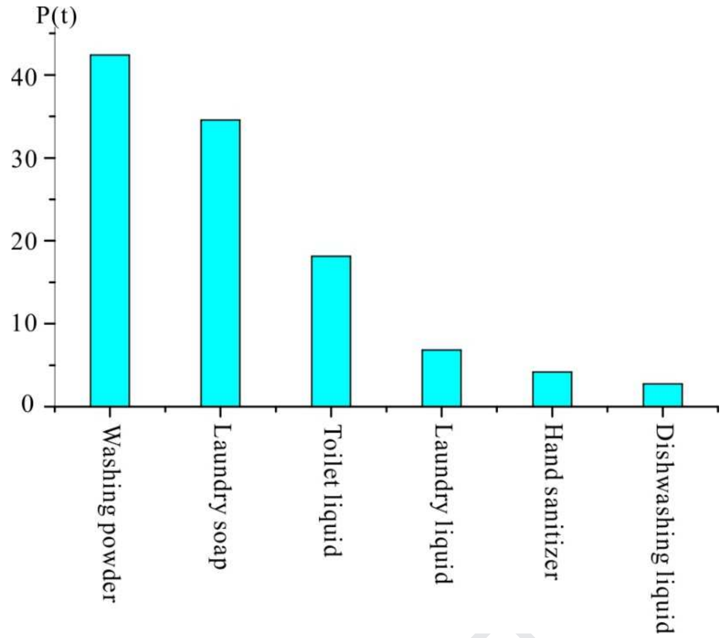

Fig. 6 P input structure of cleaning products in household consumption system of Dar es Salaam

Phosphorus input from cleaning products accounted for a relatively small proportion (2.24%) of total phosphorus input in urban household consumption system in Dar es Salaam. In the studies of phosphorus flow of urban households in China and Chaohu City, the phosphorus input of cleaning products accounted for less than 1% of the total phosphorus input(Lu, 2008; Shi, 2012). Compared with these studies, the proportion of phosphorus input from cleaning products was still high. There are mainly two reasons for this question. One is that Dar es Salaam was located in the tropical region, and the frequency of washing clothes was high during the year. The other was the habit of eating with hands. As can be seen from the Fig. 6, in the urban household consumption system of Dar es Salaam, washing powder, laundry soap and toilet cleaning liquid ranked the top three cleaning products respectively, accounting for 38.94%, 31.73% and 16.66% of phosphorus input of cleaning products. Other important phosphorous input cleaning products included laundry detergent, hand sanitizer, dishwashing liquid, etc. The phosphorus input from urban household consumption system is affected by two aspects: the quantity of material consumption and the corresponding phosphorus content. With the further advancement of urbanization and the improvement of residents' income level, the quality of life and health awareness of residents will inevitably continue to improve. Therefore, the types and quantities of detergent consumed by urban residents in the future will also increase correspondingly, and the amount of phosphorus input by the system caused by consumption of detergent will also increase.

3.2.2 Analysis of phosphorus output characteristics

Table 5 Summary of phosphorus output of urban household consumption system in Dar es Salaam (unit: t)

Type	Feces and urine	Domestic garbage	Wastewater	Food processing loss
Phosphorus output	2313	1464	561	477
Phosphorus treatment	451	1430	109	-
Phosphorus storage \ emission	1862	34	452	-

The summary results of the output of the household consumption system in Dar es Salaam were shown in the table 5. As can be seen from the table, in 2017, the total output of human feces and urine from urban household consumption system was 2313t of P, of which 451t of P was collected and treated, and the remaining 1862t of P was discharged into surface water with wastewater. Phosphorus output of domestic garbage was 1464t of P, about 97.68% of the domestic garbage was collected and treated, including 28t of P recycling, 955t of P landfill, 119t of P composting, 13t of P incineration, and 315t of P centralized storage. In addition, 34t of P is scattered and piled up without centralized treatment. Centralized storage and decentralized storage increased the risk of further phosphate loss. The wastewater of urban household consumption system discharged 561t of P, only 109t of P was collected and then enters the sewage treatment plant for treatment, and the other 452t of P was directly discharged to the surface water. The food processing loss of urban household consumption system was 477t of P, accounting for 9.90% of the total phosphorus output of the system. This part of phosphorus was finally discharged into the atmosphere. There were 2314t of P discharged into surface water through human feces and urine and domestic wastewater, which had a negative impact on the prevention and control of surface water pollution.

4. Discussion

4.1 Direction of phosphorus discharge reduction

The phosphorus input from urban household consumption system is affected by two aspects: the quantity of material consumption and the corresponding phosphorus content. Therefore, the guidance of low phosphorus consumption is an important direction of phosphorus discharge reduction.

It can be seen from the research results that a large amount of P (2348t, 48.76%) were directly discharged into the environment (Table 5) in the urban household consumption system, which showed that there were great deficiencies in wastewater treatment and garbage treatment. There is a lot of room for phosphorus discharge reduction.

4.2 Challenges of phosphorus discharge reduction

Since the beginning of the new century, the urbanization process of Dar es Salaam had accelerated. The urban population had increased from 2487300 in 2002 to 5781600 in 2017, an increase of 2.32 times, with an average annual growth of 5.78% (NBS, 2015; NBS et al., 2018). Currently, Tanzania is still in the primary stage of urbanization, with an urbanization rate of 33.78% (World Bank, 2019a). It can be predicted that the population of Dar es Salaam, as the largest city in Tanzania, will grow at a faster speed, and the corresponding input and output of phosphorus containing substance will also increase significantly, at the same time, a large number of P will emit to the surface water to pollute the environment.

Tanzania's economy developed at a relatively fast speed, with an average annual GDP growth of 6.45% during 2000-2018 (World Bank, 2019b). Dar es Salaam was the fastest growing city, with an average annual growth rate of over 10% in GDP per capita (NBS, 2019). The development of economy and the improvement of living standard will inevitably bring about the increase of animal food consumption. Residents' quality of life and health awareness will inevitably continue to improve, urban residents in the future consumption of cleaning products and the number of types will increase accordingly.

The garbage and sewage treatment capacity of Dar es Salaam was very low. According to the relevant data of the environmental statistics yearbook of Tanzania 2017, it was estimated that the garbage treatment rate was only 71.88%, and the garbage treatment was relatively simple; the domestic sewage treatment rate was only 19.5%, with low sewage treatment capacity and backward technology (NBS et al., 2018).

These challenges require environmental management policy support on the direction and deficiency of phosphorus discharge reduction.

4.3 limitations in methods and data

In terms of methods, we used the static analysis model to analyze the data of one year in Dar es Salaam, which could not evaluate the changes of phosphorus flow in time series. In terms of data, in order to realize the analysis of p-flow in the urban household consumption system of Dar es Salaam, we quoted a large number of parameters from different sources and ignored the geographical differences, which to some extent affected the accuracy of the research results. Undoubtedly, local observations and experimental analyses will greatly improve accuracy.

5. Conclusions and policy recommendations

5.1 Basic conclusions

In this study, the process of phosphorus flow in urban household consumption system was systematically analyzed from the perspective of material metabolism. By analyzing the basic mode of phosphorus flow in urban household consumption system, we established the framework of phosphorus flow analysis in urban household consumption system by means of SFA. On the basis of the establishment of the analytical framework, the accounting model of the phosphorus flow in the input, output and stock of the system was determined. We took Dar es Salaam as an example for practical application analysis, and drew the following conclusions:

(1) The total phosphorus input, stock and output of urban household consumption system in Dar es Salaam were 4874t of P, 59t of P and 4815t of P, respectively. In terms of system input of phosphorus, resident's food consumption had a decisive impact on the system's phosphorus input (4765t of P, 97.76%), while the contribution of detergent to the phosphorus input of the system was small. In terms of system phosphorus output, human feces and urine phosphorus output accounted for the majority of the total system phosphorus output (2313t of P, 48.04%). The total phosphorus output of domestic garbage, wastewater and food processing loss were 1464t of P (30.41%), 561t of P (11.65%), 477t of P (9.90%), respectively.

(2) There were 2314t of P discharged into surface water through human feces and urine and

domestic wastewater, which had a negative impact on the prevention and control of surface water pollution. 34t of P came from scattered garbage storage and 315t of P came from centralized garbage storage due to limited treatment capacity of waste treatment plant. Centralized storage and decentralized storage increased the risk of further phosphate loss.

(3) Accelerated urbanization, rapid economic development and low sewage treatment capacity would cause more phosphorus loss, and Dar es Salaam faced great challenges in P discharge reduction and pollution control.

5.2 Policy recommendations for P discharge reduction

(1) Reasonable dietary structure changes the flow direction of phosphorus (Lu, 2008). With the improvement of living standard, residents pursue reasonable dietary structure for good health. Dar es Salaam should strengthen the guidance to the reasonable dietary structure with low phosphorus.

(2) Dar es salaam should strengthen the promotion of products with less phosphorus and no phosphorus, especially the promotion of detergent powder without phosphorus, which is not only conducive to health, but also can reduce P loss.

(3) Dar es salaam should increase the capital investment in garbage treatment and sewage treatment, strengthen the construction of garbage treatment and sewage treatment infrastructure, introduce advanced treatment technology, strengthen the treatment of urban polluted rivers, and build a clean and tidy urban environment.

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