



Reaching China's fertilizer reduction goals through nitrogen and phosphorus recovery: a substance flow analysis case study

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Abstract

Linear agricultural nutrient regimes are the principal cause for perturbation of the geochemical cycles for nitrogen (N) and phosphorus (P) and other planetary boundaries. Nutrient cycles are characterized by high spatial disparity and China is a hotspot due to high fertilizer application rates. Using substance flow analysis, this study identified and quantified nutrient flows from agricultural production to residue management of Huangyan tangerines (*Citrus reticulata*) and water bamboo (*Zizania latifolia*) in a case study of Huangyan district (Taizhou City, Zhejiang province). About 754 Mg/a of N and 105 Mg/a of P can theoretically be recovered in the tangerines and water bamboo systems from currently untapped material flows. This could replace 59% of the N and 15% of the P currently applied as chemical fertilizer, reducing environmental impacts. Combining the nutrient recovery of both systems and upscaling the results to Taizhou City, the goal from the 14th Five-Year Plan for Agricultural and Rural Modernization to save 1182 Mg of nutrients per year could be exceeded by almost 12 times. This study's data have varying degrees of uncertainty. The analysis of data representativeness shows potential for improvements, especially in the agricultural production of water bamboo and the nutrient contents of material flows.

Keywords Circular economy · Nutrient management · Material flow analysis · Sustainable agriculture · Zero-growth action plan · Organic fertilizers

Introduction

The biogeochemical cycles have exceeded the proposed safe operating space for humans [1]. According to Campbell et al., agriculture is the main driver for the transgression of this and other planetary boundaries [2]. Specifically, the production of nitrogen (N) fertilizer is linked to a high energy demand (the Haber–Bosch process for ammonia synthesis is responsible for 1–2% of the world's total energy consumption) [3], it consumes 2% of the world's natural gas as feedstock [4], and contributes to 1.4% of all anthropogenic CO₂ emissions [5]. Phosphorus (P) is a finite resource mainly

mined in China, Morocco and the United States, making phosphate rock as well as phosphorus critical raw materials [6]. Apart from climate change and resource depletion, the high N and P application in agricultural regions leads to air pollution, soil acidification, and eutrophication of water bodies—which ultimately results in water dead zones, fish kills, algal blooms, and water contamination [7]. This unsustainable nutrient management attempts against the achievement the United Nations Sustainable Development Goals (e.g. 6—Clean water and sanitation, 12—Responsible consumption and production, 14—Life below water, 15—Life on land).

Industrial agricultural systems are commonly characterized by linear regimes. Since the nineteenth century, natural nutrient sources and recycled materials were no longer enough to cover the needs of the increasing population [7]. Therefore, the use of Haber–Bosch N and mined P started to increase rapidly, becoming the main nutrient input for crops—since the 1960s, the use of synthetic N fertilizers increased ninefold and the P fertilizer use tripled [7]. Although fertilizer production is concentrated in a few countries (mainly China with 25%, Russia with 10%, and

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United States and India both with 9%), its use is widely distributed globally, meaning that many countries rely on imports to cover their fertilizer demand [8, 9]. After application, an important part of these nutrients (over 80% of the N and 25–75% of the P) gets lost to the environment, causing pollution [7]. The inefficient fertilizer use has been recognized as a global issue and the UN Environment Programme highlighted the need for coordinated policies to manage N and P pollution effectively at global, national, and regional levels [10]. Moreover, fertilizers are one of the carbon-intensive products covered by the EU's Carbon Border Adjustment Mechanism (CBAM) to encourage global reduction of carbon emissions instead of moving their production to countries with less stringent climate policies [11].

China (in particular eastern China) is one of the few agricultural regions with very high P and N application rates that are the main contributors to the transgression of the biogeochemical flows boundary [1]. It is the world's largest consumer of fertilizers (42.31 Mio Mg/a of nutrients) [12], and the country with the second highest greenhouse gas (GHG) emissions from agriculture after India (663 Mio. Mg of CO₂ eq/a) [13]. The reason is that China's agriculture has been transitioning from a self-subsistence extensive agriculture to an intensive industrial cash crop production system [14]. After the establishment of the People's Republic of China in 1949, hundreds of millions of farmers were organized in collective agriculture communes, where all agriculture production decisions were made by local leaders following a higher level production plan [15]. This changed after the economic reform in 1978: collectively owned land was leased to individual farmers, who had to deliver a fixed quota of "strategic crops" to the state for a fixed price, but were also free to produce more and sell their surpluses in rural markets [15]. To increase the production on their small plots, farmers started to apply excessive amounts of chemical fertilizer—China's yearly application per hectare of cropland is one of the highest of the world with 319 kg (for comparison, the world's average is 119 kg and Europe's average, 75 kg) [16]. This resulted in a series of environmental impacts, including groundwater contamination with nitrates, eutrophication of surface waters, soil acidification, greenhouse gas emissions, loss of biodiversity, and micronutrients deficiencies in feed and food [17].

The Chinese government has set goals and introduced policies to improve sustainability in agriculture. In 2015, the Ministry of Agriculture launched the "zero-growth" action plan, regulating fertilizer and pesticide use by 2020 [18]. Later, in 2021, the 14th Five-Year Plan for Agricultural Green Development was released, emphasizing the reduction of chemical fertilizer and pesticide use and the improvement of the utilization level of agricultural resources [19]. China wants to become carbon neutral by 2060, which requires a

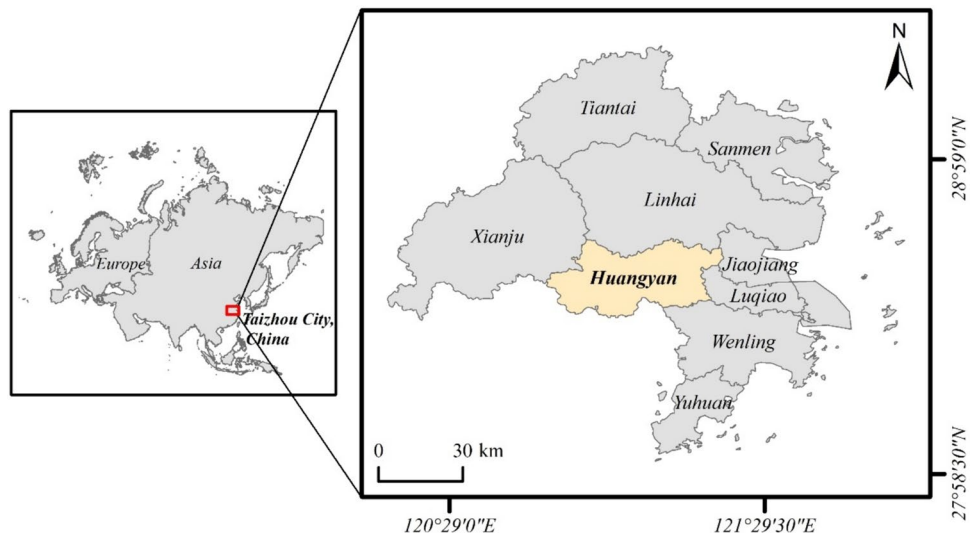
substantial transformation of the agricultural sector as well [20].

In addition, local governments are increasingly taking measures to promote agricultural practices that are more circular and sustainable. In Taizhou, a city in the Zhejiang province, the Bureau of Agriculture and Rural Affairs launched its own 14th Five-Year Plan for Agricultural and Rural Modernization to improve productivity and living standards in rural areas (its focus is slightly different of that of the national Plan for Agricultural Green Development mentioned above, which mainly aims at reducing environmental impacts). This action plan aims to increase the use of commercial organic fertilizer, digestate from anaerobic digestion, and green manure to improve soil structure and organic matter content. The utilization rate of manure (from livestock and poultry) and rice straw should also be improved to 92% and 95%, respectively, by 2025. Besides, chemical fertilizer use in the crop sector should be reduced with the help of soil testing and formula fertilization. In this way, Taizhou expects to save 0.6 kg of "pure nutrients" (N, P₂O₅, and K₂O) per Mu—or more than 1182 Mg per year—while reducing air pollution (mainly caused by straw burning), eutrophication of water bodies, soil erosion, and salinization. [21]

Implementing circular systems to achieve these goals requires the detailed study of locally available, potentially valuable organic material flows, which can be done by using Material Flow Analysis (MFA) [22]. This is a case study for Huangyan (黄岩), a district in Taizhou city (Fig. 1) [23]. Huangyan is a typical example of a region with a linear, cash-crop-oriented, agricultural system and a high demand for chemical fertilizers. While the majority of Taizhou's economic activities take place in Luqiao district, the agricultural production is based in Huangyan. The agricultural sector, with a yearly contribution of over 10 billion yuan, plays an important role in the region's economy [24]. In 2021, 1,918,000 Mu of agricultural land were sown in Taizhou, with a total output of 560,000 Mg of grain and 1,456,900 Mg of fruit [25]. By quantifying the nutrients that could be recovered in this region, the possible contribution to Taizhou's goal can be assessed and additional measures can be taken (e.g. to effectively recover those nutrients, to formulate stricter goals if necessary, or to introduce new regulations).

The study focuses on the two crops with the highest production amounts in the region, namely Huangyan tangerines (*Citrus reticulata*, annual production in Taizhou reaches 546,000 Mg/a) and water bamboo (*Zizania latifolia*, also called Manchurian wild rice, 77,000 Mg/a) [25]. Both species are native to China, which leads the global market—China produces 61% of the world's tangerines, mandarins, and clementines, and 27% of the rice [26, 27]. The goal of the study is to identify and quantify all the by-product flows

Fig. 1 Map of Huangyan, a district in Taizhou city, located in the Jiaojiang River Delta, southeast of Zhejiang Province. Huangyan has an area of 988 km² and a registered population of around 610,000



in these agri-food systems, to later derive the amounts of N and P that could theoretically be recovered and recycled. These theoretical recycling potentials will then be related to the amount of nutrients that Taizhou expects to save according to its last Five-Year Plan for Agricultural and Rural Modernization. In this way, the potential contribution of nutrient recovery in these two agri-food systems can be measured.

Materials and methods

The methodology of material flow analysis, deeply described in Brunner & Rechberger's *Handbook of Material Flow Analysis*, is defined as “a systematic assessment of the flows and stocks of materials within a system defined in space and time” [22]. MFA is an iterative method consisting of several steps, including goal and system definition (which lead to a qualitative model), determination of mass flows and stocks, and mass balance (resulting in a quantitative model). The quantified material flows can also be linked with the substances' mass fractions to identify the substance-specific sources and sinks, allowing the development of specific recommendations to improve substance flows.

Goal and system definition

The goal of this substance flow analysis (SFA) is to quantify the amount of N and P that could be recovered within the agri-food systems of the two main agricultural products (Huangyan tangerines and water bamboo) in Huangyan district, Taizhou City, Zhejiang province, China, in 2019.

The system model was defined according to the material life cycle stages identified during the data acquisition, namely: agricultural production, manufacturing, distribution and sales, consumption, and waste treatment and disposal

(Figs. 2, 3). The processes shown in the SFAs represent the average and not the best available technology. All solid organic material flows were considered. Gaseous, water, and energy flows were not regarded due to a lack of data.

Data acquisition and uncertainties

The required data were acquired by both top-down (secondary data comprising statistical and aggregated data) and bottom-up (primary data from interviews) data collection.

For the bottom-up data collection, 25 relevant stakeholders from governmental institutions, educational organizations, agricultural and manufacturing sectors, markets, and waste management companies were interviewed between October and November 2019 (supplementary material, Figure a). The interview participants were selected through snowball sampling. Interview guides were prepared in advance to provide a framework of topics to be covered (see questions in supplementary material). However, the interviews were semi-structured, including open questions and allowing new ideas to be raised during the discussion. A translator was always present to translate from Chinese to English and vice versa.

Top-down data were collected through literature research, including statistical yearbooks (from Huangyan and Taizhou), scientific publications, and official reports. This secondary data were combined with the primary data from the interviews to have a solid foundation for the MFA modelling.

For the SFA, the material composition data was taken from FoodData Central, a data system launched by the U.S. Department of Agriculture (USDA), whenever available [28]. If the needed data were not available in that system, different sources were revised, and the average of various values was calculated.

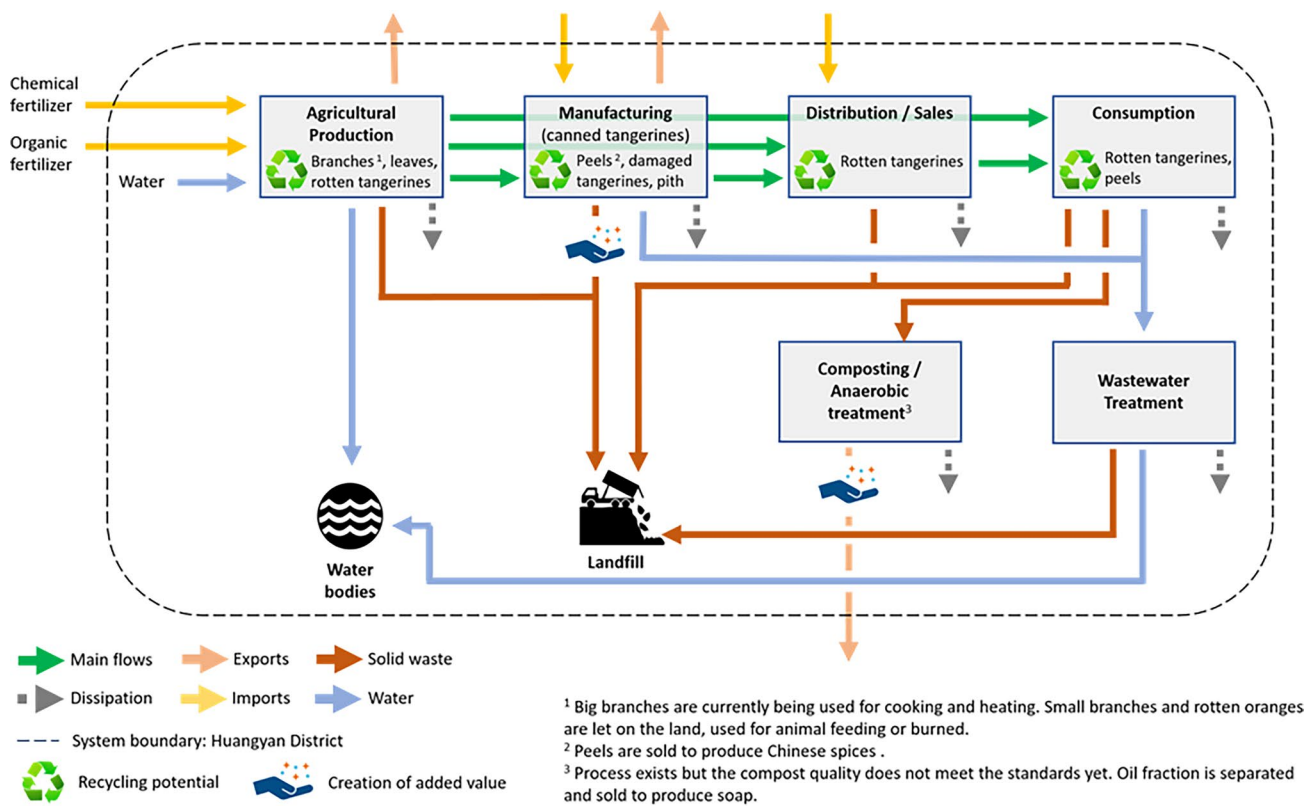


Fig. 2 System definition for Huangyan tangerines

To account for uncertainties and varying reliability, as well as the temporal and spatial representativeness of the collected data, four data representativeness levels [29] were defined to classify the quality of the gathered data (Table 1). Level 1 was assigned to educational organizations (interviewees were experts in their fields); level 2 to governmental institutions and waste treatment companies (statistical data derived from reports, measurements, and census in the study region); level 3 to farmers, food manufacturing companies and markets (specific information, not valid for the entire region); and level 4 to literature data (related to other geographic regions and/or periods).

Modelling and material balancing

Mass flows of fresh matter (FM) were determined using an *Excel* model. All the inputs and outputs of each process were related to a reference flow of 1 Mg of freshly harvested product (Huangyan tangerines or water bamboo). When a range of values was available, an average was used. The calculations to determine each of the FM flows and the assumptions made can be found in the supplementary material (Tables a, b).

The flows for the N and P SFAs were calculated by multiplying the FM flows by the N and P mass fractions of each

flow. These mass fractions were obtained from secondary sources, except for a few cases, where the interviews revealed relevant data (supplementary material, Tables c, d).

The models for Huangyan tangerines and water bamboo were introduced in the MFA software *e!Sankey* to obtain a graphical visualization of the nutrient flows. Finally, the theoretical recycling potential of P and N was calculated by adding up all the by-product flows and compared to the amount of N and P already being recycled.

These results were compared with the goal set by Taizhou's Five-Year Plan for Agricultural and Rural Modernization (saving 1,182 Mg/a of "pure nutrients"). To do that, the values for the P recycling potential were multiplied by 2.29 to account for P_2O_5 and, hence, allow the comparison with the above-mentioned goal.

Results

The results for Huangyan tangerines and water bamboo are described in this section (the graphic descriptions of the entire life cycles of the tangerines and the water bamboo can be found in Figs. 2, 3). The SFAs for N are illustrated in Fig. 4 (tangerines) and Fig. 5 (water bamboo), and those

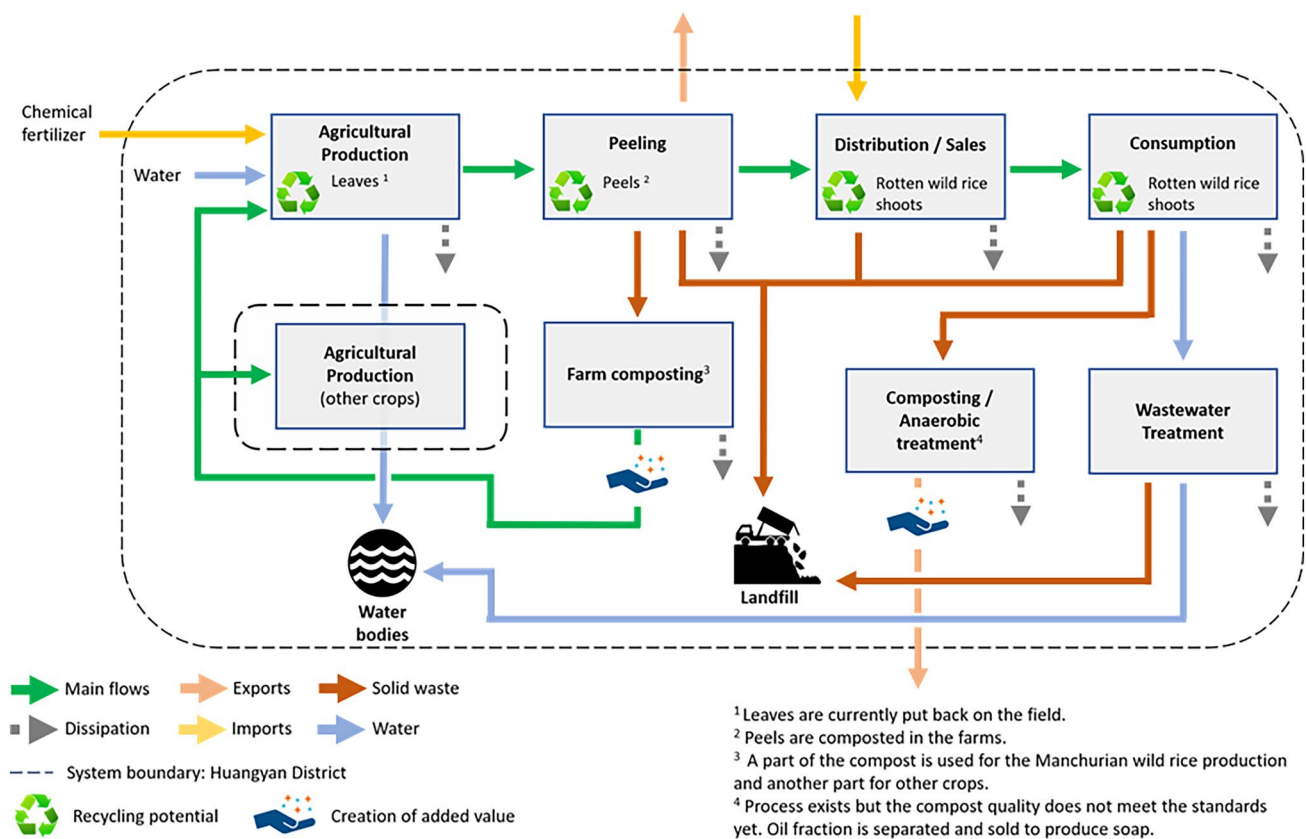


Fig. 3 System definition for water bamboo

Table 1 Overview of data representativeness levels with confidence values assigned depending on data reliability and spatio-temporal representativeness

Level	Data source	Reliability	Representativeness		Confidence values
			Spatial	Temporal	
1	Educational organizations	Very high	High	Very high	± 10%
2	Governmental institutions and waste treatment companies	High	Medium	High	± 20%
3	Farmers, food manufacturing companies and markets	Medium	Very high	High	± 30%
4	Literature data	Medium	Low	Low	± 40%

for P are shown on Fig. 6 (tangerines) and Fig. 7 (water bamboo).

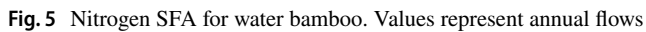
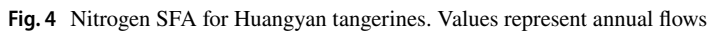
Huangyan tangerines

Agricultural production

Around 4,200 ha in Huangyan are covered by tangerine orchards. This area is shared between almost 19,500 farms, i.e. the average area of a tangerine farm in Huangyan is only 0.2 ha [24]. Most of this area belongs to families who own a small piece of land for self-supply. Recently, the government

is investing to improve the quality of Huangyan tangerines by funding large, modern tangerine gardens managed by just a few partners [30]. An average tree produces around 24 kg of tangerines per year [31]. Trees in their most productive phase, however, can produce up to 10 times more [32]. The young tangerine gardens in the district are the main reason for the low average [30].

Tangerine farmers apply 20–30% (relative to N) organic fertilizer and 70–80% chemical fertilizer (15% N, 15% P₂O₅, 15% K₂O) [31]. In 2017, Taizhou launched a policy to promote the use of organic fertilizer: farmers who use at least 50% organic fertilizer can get access to subsidies [31].



alcohol production, and compost made out of water bamboo and sugar cane waste [31, 32]. These organic fertilizers introduce 325 Mg of N and 195 Mg of P to the tangerine system.

Most of the tangerines produced in Huangyan (95%) are exported to other regions [24]. 173 Mg of N and 11 Mg of P leave the system in this way. From the rest, 95% is sold as fresh fruit directly on the farm or in markets and supermarkets (or grocery stores), and 5% serves for the further

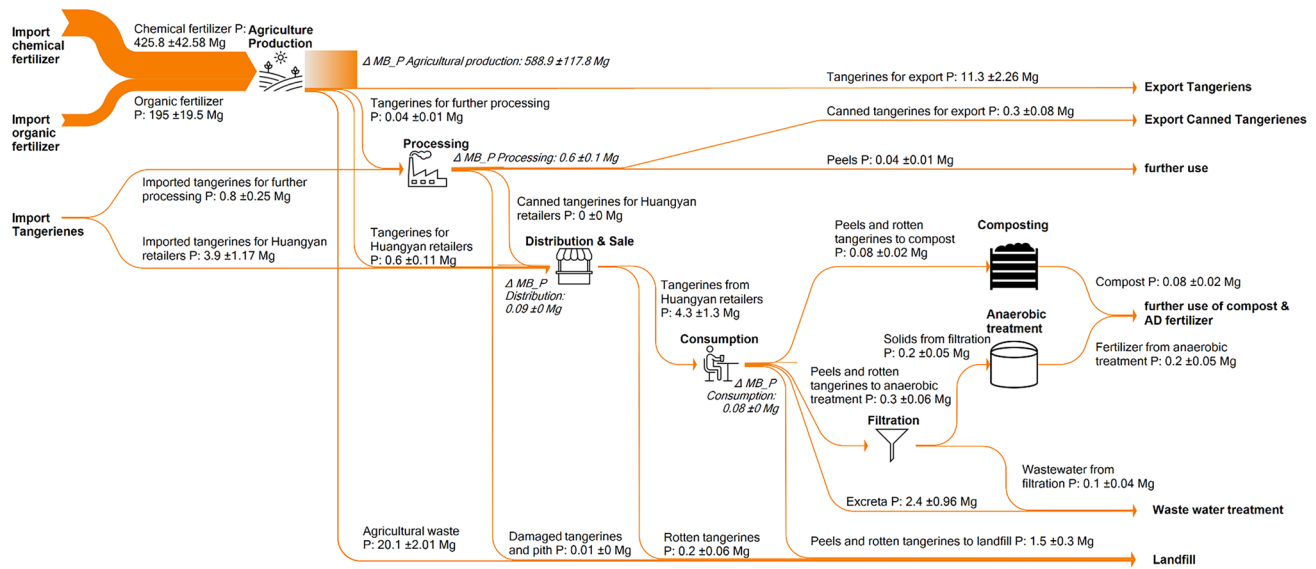


Fig. 6 Phosphorus SFA for Huangyan tangerines. Values represent annual flows

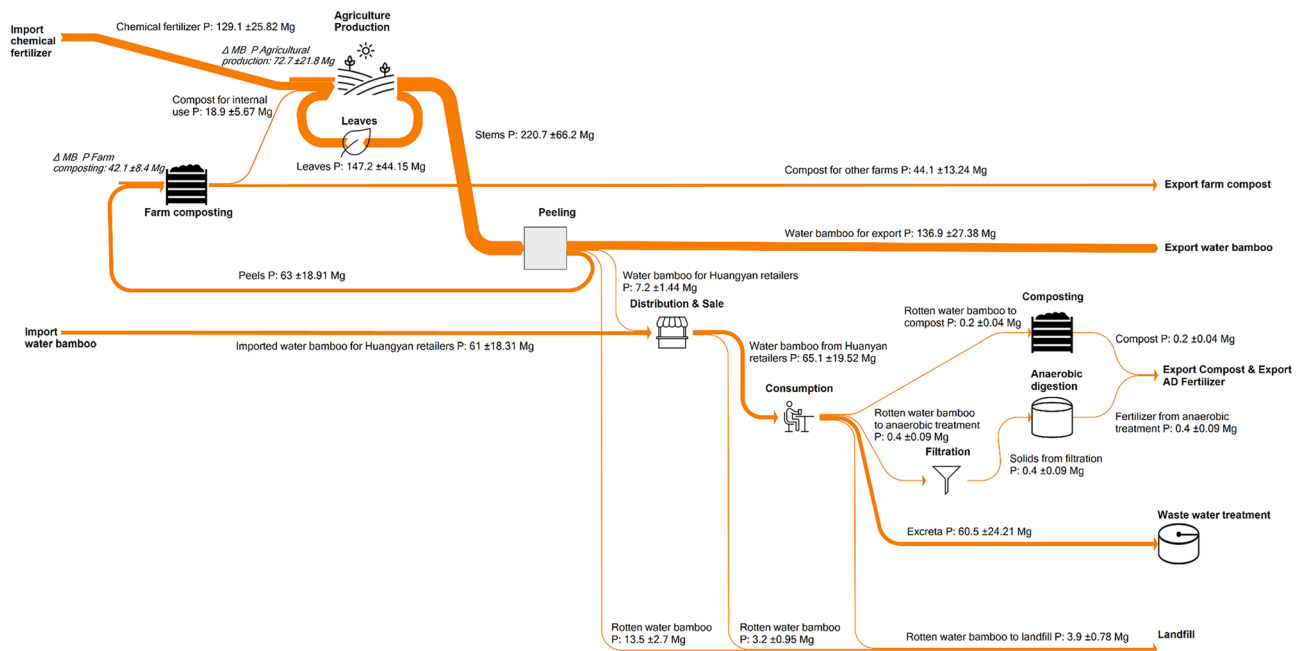


Fig. 7 Phosphorus SFA for water bamboo. Values represent annual flows

manufacturing of different products like canned tangerines, Chinese medicine, oil, or candies [33]. The largest by-product flow in the entire tangerine system comes from the agricultural stage. Every year, 16,140 Mg of by-products are produced in Huangyan's tangerine farms. This agricultural waste, consisting mostly of pruning residues, contains 311 Mg of N and 20 Mg of P. It is partly used to make fire for heating and cooking [33], while the rest is either left on the ground, burned in open fires, or landfilled [30, 31].

Farmers mentioned a lack of space (it is not permitted to construct buildings in agricultural areas) and a lack of animal manure as the main reasons why they do not compost or digest their waste [32].

Manufacturing

The biggest company for canned fruit in Taizhou City, "Yiguan Food", contributes to 10% of China's canned

tangerines production [31–34]. The majority of their products are exported and only small amounts (5%) stay in Taizhou for supermarkets, cake and jelly production [35]. The tangerines for the manufacturing process are purchased from different cooperatives in Taizhou, Hubei, Hunan, and, mostly, Linhai [36]. The production process includes size separation (small tangerines are picked out), heating in water to facilitate the peel separation, and an acid–base treatment to separate the pith. Afterward, tangerines are separated into slices by hand, which in some cases damages them. Peels, damaged or rotten tangerines, pith, and wastewater are the major by-product flows in this production chain. The peels are sold to a company that produces spices. Wastewater is sent to an industrial treatment plant that processes wastewater from this and other companies, before going to the municipal wastewater treatment plant.

Distribution

Huangyan's tangerines for fresh consumption are either sold directly from the farm (30%) or in markets and supermarkets (70%) [37]. Only 9% of the products in the market come from Huangyan, while the rest is imported from other regions, for example from the wholesale market in Luqiao [38]. Imported tangerines introduce 60 Mg of N and 4 Mg of P into the system. Around 5% of the products sold in the market get wasted [39]. A small part of these by-products is collected by people who use it to feed their animals, but most of it goes to Huangyan's landfill [40]. In contrast, the wholesale market in Luqiao treats part of its by-products: the “clean” fraction (without plastic, paper, or other contaminants) is treated at high temperatures to produce fertilizer. The “contaminated” fraction is compressed. The wastewater then goes to the wastewater treatment plant and the compressed waste is incinerated at Luqiao waste to energy plant. [39]

Consumption

Around 6% of the produced tangerines, containing 50 Mg of N and 2 Mg of P, get wasted in households [41]. The consumed nutrients are excreted and leave the households with the wastewater (16 Mg of N and 2 Mg of P).

Waste treatment

Huangyan Waste Sorting and Treatment Centre is responsible for 20% (or 27 Mg per day) of municipal perishable waste. Well-sorted perishable waste from school and office canteens, as well as the “clean” fraction of the perishable household waste is composted. This accounts for 20% of the perishable waste treated by the company. The composting process is still being tested, and the compost quality is

still not good enough for agricultural applications. The rest 80% of the company's perishable waste, corresponding to the “polluted” fraction of the household waste, is treated anaerobically. This waste is first filtered, and then the oil is separated and sold to soap or biodiesel companies. The solid fraction is treated for three to seven days under anaerobic conditions and high temperatures (around 140 °C), while the liquid fraction goes to the wastewater treatment plant. Also this treatment is still being tested to improve the quality of the resulting fertilizer. [42]

Most of Huangyan's municipal perishable waste (80%) ends up in the landfill [42]. 40 Mg of N and 2 Mg of P get lost in this way. At the time of the field trip, the landfill was almost full, and a new incineration plant was being constructed to replace it. During the interview at the landfill, it was stated that China would ban landfills in 2020. There was a project to use kitchen waste to produce biogas in the future, but there was still no estimated starting date. [43]

Wastewater treatment

Excreta is the main waste flow resulting from the tangerine consumption stage, and the second-largest waste stream in the entire system (12,009 Mg/a). Yuanqiao wastewater treatment plant in Huangyan District can treat up to 60,000 m³ per day. The site covers an area of more than 11 ha and applies Anaerobic/Anoxic/Oxic technology (AAO). The clean effluent is discharged into the river. [44]

Water bamboo

Agricultural production

Manchurian wild rice (*Zizania latifolia*), or water bamboo, is a perennial plant native to China [45]. Its seeds have been consumed as a cereal for more than 3,000 years. When infected with the black smut fungus (*Ustilago esculenta*), the stem becomes bigger and tender, making it the second most-cultivated aquatic vegetable in China. Huangyan is one of the main producing areas in the country [46]. Wetland farms growing *Z. latifolia* in Huangyan cover a much smaller area than tangerine farms—around 800 ha [37]. However, this area is growing because producing this crop in paddy fields is more profitable than producing rice [30].

There are two harvest seasons for water bamboo: one from May to June and another one from October to December [47]. In the summer, the production (around 100 kg/ha) is twice as much as in autumn [48]. To produce 1 Mg of water bamboo, farmers use on average 50 kg of chemical fertilizer (15–15–15) [24]. In this way, 296 Mg of N and 129 Mg of P are added to the cropland every year. Apart from that, in the summer, farmers put compost from their

farms back in the field (503 Mg of N and 19 Mg of P per year) [48].

During the harvesting, waste leaves (which represent 30% of the plant's weight) are cut off and, in most cases, left on the field [47]. This is the heaviest by-product flow in the entire system, accounting for 25,200 Mg per year (437 Mg of N and 147 Mg of P). There are some farms using these leaves to cover the soil (e.g. in tangerine fields) to improve its quality, although the transport and labour is expensive [49]. Stems are collected for further processing [47]. In the next step, the stems are peeled by hand. Thus, the water bamboo shoots (representing 50% of the plant's weight) are separated from the peels (accounting for the rest 20%) [47].

Around 20 kg/ha of water bamboo shoots are wasted every year because of diseases, bad quality, or bad appearance. This agricultural waste stream, containing 64 Mg of N and 14 Mg of P, gets landfilled [24]. After the peeling process, the majority of the water bamboo shoots are exported, along with 648 Mg of N and 137 Mg of P. This is the largest P export in the system.

Farm composting

The peels are cut into little pieces on site and mixed with urea—the largest nitrogen flow in the system, adding 3,091 Mg of N—and decomposing agent. After 20 days, the compost is ready to be put back on the field. This is done every year at the end of July. 70% of the compost (1173 Mg of N and 44 Mg of P) is sent to other fruit and vegetable farms, constituting the largest N export in the system. The rest 30%, containing 503 Mg of N and 19 Mg of P, is used in the farm itself. [48]

Distribution

Most of the produced water bamboo shoots (95%) are exported to other regions. The part that stays in Huangyan gets sold in markets, supermarkets, and grocery stores [24]. As mentioned for the tangerine system, only 9% of the products in the markets come from Huangyan, and about 5% of the products sold in the market get wasted.

Consumption, waste treatment, wastewater treatment

The life stages consumption, waste treatment, and wastewater treatment are identical to the ones described for the tangerine system. Also in, this case, excreta constitutes the major waste flow coming from the consumption stage (16,032 Mg/a). 286 Mg of N and 61 Mg of P are lost through this route.

Recovery potentials

In the tangerine system, the by-product streams that could theoretically be recycled include agricultural waste; peels, damaged tangerines, and pith from the manufacturing process; and excreta, peels, and rotten tangerines from the consumption process. These flows amount to 38,870 Mg/a. The nitrogen content in those flows adds up to 382 Mg/a and the phosphorus content to 25 Mg/a.

Only the tangerine peels from the manufacturing process are currently being recycled to produce spices and a part of the rotten tangerines and peels from consumption are treated anaerobically or through composting. These account for 2,115 Mg/a or 5% of the total theoretical recycling potential. The nitrogen contained in the recycled flows accounts for only 11 Mg/a or 3%, and the phosphorus for 0 Mg/a or 2% (Fig. 8).

Regarding the water bamboo system, the theoretically recyclable by-product streams include leaves cut and put back into the field while harvesting; peels and rotten water bamboo from the peeling process; rotten water bamboo from the markets; and excreta and rotten water bamboo from consumption. Together, these flows amount to 63,685 Mg/a. The nitrogen content in those flows adds up to 1,122 Mg/a and the phosphorus content to 292 Mg/a.

The materials that are already recycled include water bamboo leaves and peels in the field and rotten water bamboo shoots that are sent to composting or anaerobic treatment after consumption. These flows add up to 42,166 Mg/a, or 66%, of the theoretical recycling potential for fresh matter. The nitrogen contained in the recycled flows accounts for 738 Mg/a or 66%, and the phosphorus for 211 Mg/a or 72% (Fig. 8).

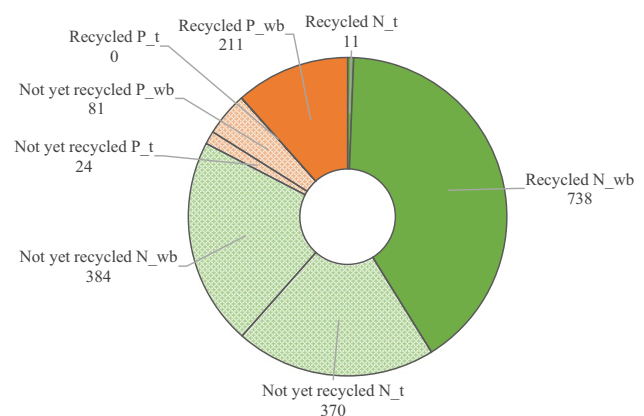


Fig. 8 Tapped and untapped recycling potential for nitrogen and phosphorus in Huangyan's tangerine and water bamboo systems. Solid color areas represent the amount of N (green) and P (orange) that is already being recycled. Dotted areas represent the amount of N (green) and P (orange) that is not yet recycled. *t* tangerine system, *wb* water bamboo system

Contribution to Taizhou's goal

Adding up the recycling potentials of the untapped N and P_2O_5 flows results in 426 Mg/a for Huangyan tangerines and 570 Mg/a for water bamboo (Fig. 9). The goal of Taizhou's Bureau of Agriculture and Rural Affairs is to save 1,182 Mg of “pure nutrients” (N, P_2O_5 , K_2O) per year. Hence, recovering all the N and P from the analysed systems would contribute 36% to the achievement of the goal in the case of the tangerines and 48% in the case of the water bamboo. Combining both systems would make a very high contribution to the goal (84%).

Discussion

Data uncertainties of material flows

The basis for the N and P SFAs for tangerines and water bamboo presented in Sect. “Results” are MFAs conducted in the scope of this study. Data uncertainties for the corresponding material flows are discussed hereunder. The below-mentioned reference flows correspond to 1 Mg of fresh matter (tangerines or water bamboo).

Data uncertainties in the tangerine system

The data representativeness of all flows entering or leaving the agricultural production process in the tangerine's SFA corresponds to the first or the second level. The “organic fertilizer” input and the “pruning residues and leaves” output account for 21% of the reference flow. The size of these flows combined with their very high data reliability form a good basis for the SFA. The flow “tangerines for export” is the largest of the system, accounting for 90% of the reference

flow, and it is defined with high reliability. Due to the flows' significance, it is recommended to further improve data representativeness and confirm flow quantities by published scientific data or an independent source such as producers or distributors. Most input and output data of the canned tangerines production process was provided by one factory owner (*Yiguan Food*) and therefore was classified as medium reliability data. It could be argued that in reality data representativeness is higher, since it is the largest company producing canned tangerines in Taizhou City [31–34]. Further research could be conducted by examining other similar factories or conducting own measurements. The largest flow related to this process, however, only accounts for 7% of the reference flow. Hence, efforts to improve the data quality of this process should be kept within reasonable limits. Three of the four flows of the distribution process correspond to the third data representativeness level. Due to the significance of the “imported tangerines” (31% of the reference flow) and the “tangerines for the markets” (33%) flows, it is suggested to verify the gathered information. More interviews with owners of various markets in Huangyan should be conducted. It was assumed that the consumers are “steady state” humans, i.e. the nutrients consumed in the food will end up in the excreta, based on the fact that the percentage of food retained by the human body for the synthesis of tissues can be considered negligible on average [50]. Since this data comes from literature, those flows were classified as level four. The “Excreta to wastewater” flow is the largest output (1% of the reference flow) of the consumption process. Its data with defined medium data reliability was obtained from scientific publications of other geographic regions and periods. Since this flow holds a significant nutrient recovery potential, it is recommended to reduce data uncertainty and contact Taizhou's Environmental Protection Bureau. Unfortunately, during this study, the Bureau repeatedly refused to be interviewed. Requesting a reference letter from the Chinese government could help to obtain data from governmental institutions. All the flows entering and leaving the composting, filtration, and anaerobic treatment processes belong to the data representativeness level 2, which indicates that these flows can picture the real situation in Huangyan relatively well.

Data uncertainties in the water bamboo system

The outputs of the agricultural production, “stems” and “leaves” account for 140% and 60% of the reference flow, respectively. Both flows are based on data from one farmer and are, therefore, defined as the third data representativeness level. Roughly 29% of the stems become peels. Together with the amount of rotten water bamboo shoots, it makes ca. 53%, which corresponds with the information obtained from Huangyan Agricultural Bureau—according

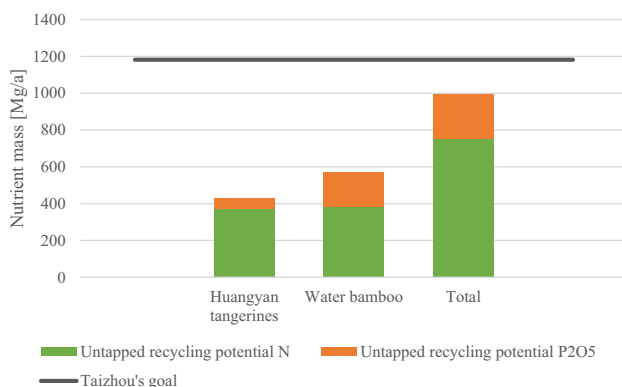


Fig. 9 Contribution of the potentially recyclable N and P_2O_5 in both Huangyan systems (Huangyan tangerines and water bamboo) to the goal set by Taizhou's Five-Year Plan for Agricultural and Rural Modernization on the mass of “pure nutrients” (N, P_2O_5 , K_2O) to be saved

to which 50% of the vegetable is wasted [30]. The “leaves” and the “peels” flows are the largest by-product flows in the system and represent the highest nutrient recovery potential. Based on the statements of two farmers (third representativeness level) the leaves are left in the fields during the harvest and the peels are composted. It is recommended to approach water bamboo experts (equivalent to the scientists from the Institute of Citriculture for the tangerines), identify relevant scientific studies, or conduct surveys covering a representative number of farms, to reduce data uncertainty for these relevant material flows. The data employed to model the rest of the processes (distribution, consumption, composting, filtration, and anaerobic treatment) is the same as the one used for the tangerines. Hence, the data representativeness of those processes in both systems is similar and the same recommendations can be drawn (see “[Data uncertainties in the tangerine system](#)”).

Data uncertainties in both systems

The fresh matter flows served as a basis for the calculation of the N and P flows. During the SFA modelling, the uncertain material flow values were multiplied by estimates for N and P contents obtained from secondary sources. Firstly, the level of uncertainty rises with these mathematical operations. Secondly, the values from the literature refer to studies with different spatial scopes decreasing the accuracy of the calculated P and N flows in this study. To improve accuracy and reduce uncertainty, it is recommended to conduct a sampling campaign to measure the N and P contents of each flow as a basis for the SFAs, as was done in a Danish study [51]. Although this approach would have exceeded the scope of this study, it could have avoided the need for several assumptions (supplementary material, Tables c, d).

Methodological uncertainties of the material and nutrients SFAs

The inputs and outputs of the substance flow processes are not always balanced (see Δ MB flows in the SFAs), since data on energy, soil, water, and gas flows could not be gathered in the scope of this study. The following two paragraphs discuss nutrient imbalances. The mentioned values represent the real annual flows in Huangyan.

Methodological uncertainties in the tangerine system

The biggest N losses occur as agricultural waste during the tangerine production (311 ± 31 Mg/a) and as peels during the consumption phase (50 ± 10 Mg/a). The N mass fraction of the peels is higher than that of the rest of the fruit. Since most of the peels produced during the consumption phase (80%) are sent to the landfill, this organic material

is lost from the system. 807 ± 161 Mg N/a are missing when comparing N from fertilizer application (inputs) and N contents in agricultural products and by-products (outputs). From the applied $1,300 \pm 130$ Mg N/a, only 13% (173 ± 35 Mg/a) end up in the tangerines. The findings align with previous research, which shows that agriculture is responsible for almost three quarters of all N losses (43% of those losses occur through nitrate leaching to ground and surface waters, 30% through denitrification, and 23% through ammonia emissions) [52]. Similarly, major P losses in the tangerine system occur during agricultural production. While 621 ± 62 Mg P/a are applied to the tangerine fields, 20 ± 2 Mg/a end up in agricultural waste and 12 ± 2 Mg/a (2%) in produced tangerines. The rest 589 ± 118 Mg P/a (95%) is lost. Prior research has also showed that more than half of the total P losses happen in agriculture, 88% of those losses through P accumulation in soils [52]. According to George [53], agricultural production has low P-efficiencies due to solubility and mobility interactions in soils and plants. Also, Golomb and Goldschmidt [54] stated that less than half (43.7%) of the P-uptake by the mandarin trees ends up in the fruits. The pruning residues and leaves to product ratio calculated in a Croatian study is much lower than the one resulting from this study (0.07 kg/kg versus 0.21 kg/kg) [55]. This can be explained by the new tangerine farms in Huangyan, since young trees have lower production rates leading to relatively higher amounts of residues [30]. The pruning residues and leaves to product ratios are expected to decrease in the future, with more mature trees. These are also possible reasons for the low N-uptake of tangerines in Huangyan. Furthermore, the export of tangerines implies N and P losses for Huangyan’s tangerine system, with 176 ± 36 Mg N/a (14%) and 12 ± 2 Mg P/a (2%). No information was found on the local wastewater treatment processes. The literature research indicated that wastewater treatment plants in China are still concerned about removal—and not recovery—of nutrients, and that landfilling is the main sludge treatment method [56]. Hence, the nutrients contained in excreta (16 ± 6 Mg N/a, 2.4 ± 1.0 Mg P/a) are not recovered. A study conducted in Vietnam quantified regional N and P flows from rice, fruit, and vegetable production. Major P losses modelled in that study also occur during the same life cycle stages and include leachate from agricultural production, solid waste, and excreta from households [57]. Analyses of soil, surface water, groundwater, and wastewater samples, as well as liquid and gaseous emissions, could provide details on the fate of N and P in the agricultural production and consumption phase.

Methodological uncertainties in the water bamboo system

The production of water bamboo is characterized by higher N and P recovery rates than that of tangerines. Assuming

that all nutrients from the leaves, which are cut off during the harvest process, are absorbed by the crops in the wetland, a total of 29% N (550 ± 165 Mg/a) and 56% P (166 ± 50 Mg/a) of the applied nutrients would be recovered. The differences between added nutrients from fertilizer and leaves (inputs) compared to harvested stems (outputs) are 425 ± 127 Mg N/a (22% of applied N) and 73 ± 22 Mg P/a (20%). Other studies investigating flooded rice production systems, showed that the largest losses for P and N were caused by run-off, leaching and accumulation in the soil, as well as emissions to air [58, 59]. These potential nutrient losses should be quantified in future studies for the water bamboo production system with leaves decomposing in anaerobic conditions in flooded paddies and peels further processed to compost (19 Mg P/a).

The nutrient losses during the peeling, distribution and consumption phase are 384 Mg N/a and 81 Mg P/a from rotten water bamboo and excreta, which end up in the landfill or the wastewater treatment plant. 50% of the N ($1,821 \pm 481$ Mg/a) and 95% of the P (181 ± 41 Mg/a) entering the system as fertilizers are exported as water bamboo and composted leaves.

In summary, for the agricultural processes, nutrient fixation in soil and nutrient leaching in surface and ground water, as well as gaseous emissions, are assumed to be relevant contributions to the substance imbalances. For the remaining processes, data uncertainties are assumed to be the main cause for imbalances. The N and P SFAs presented in this study, as well as the derived recycling potentials, should be considered as estimates. It is strongly recommended to conduct a sampling campaign and use own measurements to correct these results.

Contribution to the Chinese national and regional political goals towards a sustainable agriculture

The results suggest that, combining the already recycled streams with the currently unutilized rotten tangerines and water bamboo as well as the resulting excreta from consumption, over 1,503 Mg N/a and 316 Mg P/a (725 Mg P_2O_5 /a) could theoretically be recovered in Huangyan. Recovering these nutrients would allow a growth of agricultural production of 15% (based on N) and 13% (based on P), while fulfilling the zero-growth action plan of the Chinese government. Upscaling these results from Huangyan district to the region of Taizhou, 11,065 Mg N/a and 1,329 Mg P/a ($3,043$ Mg P_2O_5) could theoretically be recovered (based on the production numbers for tangerines and water bamboo published in Taizhou's statistical yearbook) [60]. Adding up the nutrient mass for N and P_2O_5 then results in 14,108 Mg nutrients/a. This would exceed the goal of chemical fertilizer reduction (1,182 Mg of nutrients) by almost 12 times. It is worth mentioning that this result would be even better if potassium flows would have also been accounted for. Considering the

negative environmental impacts caused by the utilization of chemical fertilizers [61, 62], recycling activities can help to enhance environmental sustainability and support China in becoming carbon neutral in 2060.

Challenges and measures for practical implementation of nutrient recovery

While this study calculates the theoretical potential for nutrient recovery, several practical challenges must be addressed to enhance feasibility. Primarily, technical barriers exist, such as the efficiency of recovery technologies. For example, net losses of 18% of N were reported during anaerobic digestion [63], and for composting they can reach up to 50% [64]. Besides, the agricultural by-products analyzed in this study are from plant origin, and an addition of animal manure (which could imply a collaboration with other stakeholders) might be required to improve the efficiency of the recovery process. These technologies depend on (in some cases advanced) infrastructure and expertise, requiring investment in training and capacity-building for local technicians and farmers. Economic constraints also play a significant role: the initial investment costs for installing nutrient recovery systems can be a big barrier. As a reference, a household-scale biogas digester in China costs between 368 and 792 USD [65]. To encourage adoption, financial incentives such as subsidies or low-interest loans could be provided.

An important condition for stakeholders to adopt technologies to treat organic wastes for bio-based fertilizers' production is that there needs to be a market for those fertilizers. Users of organic fertilizers have high quality expectations (nutrient content, nutrient release rates, risk) [66]. Moreover, a Chinese study on barriers to replace mineral fertilizers with manure showed that farmers have an overall negative attitude, lack of knowledge, and limited experience [67]. Targeted marketing strategies that provide information on the benefits and costs of implementation are needed, as well as regulatory tools that ensure price stability (to maximise the market share of these fertilizers, they should be 30–46% cheaper than equivalent mineral fertilizers) [68]. Sutton et al. [7] stress the importance of a holistic approach to nutrient management, advocating for improved nutrient use efficiency throughout the entire food chain to enhance food and energy production while minimizing losses that cause environmental impacts.

Conclusion

This study quantifies untapped theoretical recycling potentials for N and P throughout the tangerine and water bamboo life cycle in Huangyan, China in 2019 (370 ± 47 Mg N and 24 ± 3 Mg P for tangerines, and 384 ± 136 Mg N

and 81 ± 29 Mg P for water bamboo). Hotspots for nutrient recovery include inefficient agricultural residue utilization, low recovery of nutrients from organic residues in municipal solid wastes (most N and P is landfilled), and missing recovery of N and P during wastewater treatment. N and P imports of 427 ± 128 Mg/a for tangerines and water bamboo production are contrasted by N and P exports of $2,189 \pm 560$ Mg/a. Such imbalances are symptomatic for cash crop producing regions and result in the need of chemical fertilizer imports. Implementing circular economy management approaches such as precision farming, source waste separation, composting, or anaerobic digestion, combined with advanced wastewater treatment concepts could improve N and P recovery.

The recovery of these nutrients could substitute 59% of N and 15% of P supplied by chemical fertilizers for tangerines and water bamboo production in Huangyan, contributing to the circular economy and the achievement of political goals in Taizhou and China. Using untapped nutrients enables further production growth while reducing chemical fertilizer application, contributing to the zero-growth action plan of the Chinese Ministry of Agriculture. The use of organic fertilizers from agricultural residues and municipal solid waste and wastewater allows low-carbon agriculture and improvement of the utilization level of agricultural resources in line with the 14th 5-year plan of the Chinese government, paving the path towards carbon neutrality in 2060. On a regional level, implementing these circular concepts would allow Taizhou to reach the goal of increasing the use of organic fertilizer, digestate from anaerobic digestion, and green manure; improving soil structure and organic matter content. Taizhou could exceed the expected nutrients saving of 0.6 kg (sum of N, P_2O_5 and K_2O) per Mu—or more than 1,000 Mg per year (worth over 5 million yuan)—reducing air pollution (mainly caused by straw burning), eutrophication of water bodies, soil erosion and salinization.

Reliable data are crucial for potential assessments, yet currently available Chinese data for regional material and substance flows stems from statistical yearbooks, which lack scientific basis. To address this uncertain data foundation, this study defines data representativeness levels. This enables a first quantification and visualization and supports the identification of data weak points for future studies to address. The study identified theoretical recycling potentials, but several challenges related to technology efficiencies, costs, and users' acceptance need to be addressed to ensure feasibility.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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References

1. Steffen W, Richardson K, Rockstrom J et al (2015) Planetary boundaries: guiding human development on a changing planet. *Science* 347:1259855–1259855. <https://doi.org/10.1126/science.1259855>
2. Campbell B, Beare D, Bennett E et al (2017) Agriculture production as a major driver of the earth system exceeding planetary boundaries. *Ecol Soc*. <https://doi.org/10.5751/ES-09595-220408>
3. Tanabe Y, Nishibayashi Y (2013) Developing more sustainable processes for ammonia synthesis. *Coord Chem Rev* 257:2551–2564. <https://doi.org/10.1016/j.ccr.2013.02.010>
4. Cherkasov N, Ibadon AO, Fitzpatrick P (2015) A review of the existing and alternative methods for greener nitrogen fixation. *Chem Eng Process Process Intensif* 90:24–33. <https://doi.org/10.1016/j.cep.2015.02.004>
5. Capdevila-Cortada M (2019) Electrifying the Haber-Bosch. *Nat Catal* 2:1055–1055. <https://doi.org/10.1038/s41929-019-0414-4>
6. European Commission (2020) Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions—critical raw materials resilience: charting a path towards greater security and sustainability
7. Sutton MA, Bleeker A, Howard CM et al (2013) Our nutrient world: the challenge to produce more food and energy with less pollution. Global overview of nutrient management. Centre for Ecology and Hydrology, Edinburgh
8. U.S. Department of Agriculture (2022) Impacts and repercussions of price increases on the global fertilizer market. Foreign Agricultural Service, Washington DC
9. FAO (2022) The importance of Ukraine and the Russian federation for global agricultural markets and the risks associated with the war in Ukraine. Food and Agriculture Organization of the United Nations, Rome

10. UNEP (1995) Programme of action for the protection of the marine environment from land based activities
11. European Commission (2023) Carbon border adjustment mechanism. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en. Accessed 24 Jun 2024
12. Statista (2024) Consumption of fertilizers worldwide in 2021, by country. In: Statista. <https://www.statista.com/statistics/1287852/global-consumption-fertilizer-by-country/>. Accessed 25 Jun 2024
13. OECD (2022) Agricultural policy monitoring and evaluation 2022: reforming agricultural policies for climate change mitigation. OECD, Paris
14. Wang S, Li D, Li T, Liu C (2021) Land use transitions and farm performance in China: a perspective of land fragmentation. *Land* 10:792. <https://doi.org/10.3390/land10080792>
15. Lohmar B, Gale F, Tuan F, Hansen J (2009) China's ongoing agricultural modernization: challenges remain after 30 years of reform. United States Department of Agriculture, Washington, DC
16. Ritchie H, Roser M, Rosado P (2022) Fertilizers. Our World Data
17. van Wesenbeeck CFA, Keyzer MA, van Veen WCM, Qiu H (2021) Can China's overuse of fertilizer be reduced without threatening food security and farm incomes? *Agric Syst* 190:103093. <https://doi.org/10.1016/j.agsy.2021.103093>
18. Shuqin J, Fang Z (2018) Zero growth of chemical fertilizer and pesticide use: China's objectives, progress and challenges. *J Resour Ecol* 9:50–58. <https://doi.org/10.5814/j.issn.1674-764x.2018.01.006>
19. FAO (2022) 14th five-year national agricultural green development plan. In: Food Agric. Organ. U. N. <https://www.fao.org/faolex/results/details/en/c/LEX-FAOC205820/>. Accessed 16 Nov 2022
20. Hou J, Hou B (2019) Farmers' adoption of low-carbon agriculture in China: an extended theory of the planned behavior model. *Sustainability* 11:1399. <https://doi.org/10.3390/su11051399>
21. Taizhou's Bureau of Agriculture and Rural Affairs (2021) 14th five-year plan for agricultural and rural modernization in Taizhou. Taizhou
22. Brunner PH, Rechberger H (2016) Handbook of material flow analysis: for environmental, resource, and waste engineers, second edition, 2nd edn. CRC Press, Boca Raton
23. Huangyan District Statistics Bureau (2024) Huangyan district statistical report on national economic and social development in 2023. Huangyan
24. Taizhou Agricultural Bureau (2020) Overview of agriculture and rural areas. In: Taizhou Agric. Bur. http://nyncj.zjtz.gov.cn/art/2020/5/25/art_1229051573_1919.html. Accessed 22 Jul 2020
25. Taizhou Municipal Bureau of Statistics (2022) Taizhou 2021 national economic and social development statistical bulletin. Taizhou
26. FAO (2023) Crops and livestock products
27. Guo HB, Li SM, Peng J, Ke WD (2007) *Zizania latifolia* Turcz. cultivated in China. *Genet Resour Crop Evol* 54:1211–1217. <https://doi.org/10.1007/s10722-006-9102-8>
28. U.S. Department of Agriculture (2020) Search result for tangerine, raw. In: FoodData Cent. <https://fdc.nal.usda.gov/fdc-app.html#/food-details/1102601/nutrients>. Accessed 13 Nov 2020
29. Moss RH, Schneider SH (2000) Uncertainties in the IPCC TAR: recommendations to lead authors for more consistent assessment and reporting. World Meteorol Organ
30. Wang Y, Yang X, Chen K, et al (2019) Interview with various members of Huangyan Agriculture and Forestry Bureau
31. Fang, Lu, Cao, Li (2019) Interview with various members of the Institute of Citriculture at Zhejiang Academy of Agricultural Sciences
32. Tao Y (2019) Interview with Mr. Tao, Director of the Seed Management Department at Xihe Ecological Agriculture Development Co.
33. Cheng (2019) Interview with Mr. Cheng, Head of Fengyan Village, at Huangyan Duanjiang orange cooperative
34. Zhao GF (2019) Interview with Mr. Zhao, Director of the Agriculture Institute, at Taizhou Vocational College of Science and Technology
35. Ni, Wu, Ke, Xu (2019) Interview with various members of Taizhou Agricultural Leading Enterprises Association (TALEA)
36. Ke (2019) Interview with Mr. Ke, General Manager of Taizhou Yiguan Food Co. Ltd.
37. Huangyan Agriculture and Forestry Bureau (2020) German-Chinese cooperation "Urban-Rural Assembly". Organic recycling questionnaire
38. Xu (2019) Interview with Ms. Xu, Vice Head of the Department of Commercial Crops, at Taizhou Agricultural Bureau
39. Zhang XF (2019) Interview with Mr. Zhang Xue Feng, manager of Luqiao market
40. (2019) Interview with various sellers at Huangyan market
41. Piesse M (2017) The Wasteful Dragon: Food Loss and Waste in China. Future Dir Int Pty Ltd
42. Zhang K (2019) Interview with Mr. Zhang, Project Manager of Vortex Technology Co., Ltd.
43. Yu H (2019) Interview with Mr. Yu, engineer at Huangyan Waste Ecological Landfill
44. China Wastewater Treatment Engineering Network (2017) Huangyan district yuangiao sewage treatment plant. In: China wastewater Treat. Eng. Netw. <https://www.dowater.com/company/2017-05-18/552508.html>. Accessed 21 Nov 2020
45. Leschen W (2018) Thematic background study—genetic resources for farmed freshwater macrophytes: a review
46. Yan N, Du Y, Liu X et al (2018) Morphological characteristics, nutrients, and bioactive compounds of *Zizania latifolia*, and health benefits of its seeds. *Molecules* 23:1561. <https://doi.org/10.3390/molecules23071561>
47. Xie (2019) Interview with Mr. Xie, owner of Beiyang Manchurian wild rice farm
48. Yang L (2019) Interview with Mr. Yang, owner of Liang Jun Manchurian Wild Rice Farm
49. Tao K (2019) Interview with Mr. Tao, owner of Juyuandi farm
50. Muñoz I, i Canals LM, Clift R, Doka G (2007) A simple model to include human excretion and wastewater treatment in life cycle assessment of food products. *Cent Environ Strategy Univ Surrey Guildf Surrey*
51. Jensen MB, Møller J, Scheutz C (2017) Assessment of a combined dry anaerobic digestion and post-composting treatment facility for source-separated organic household waste, using material and substance flow analysis and life cycle inventory. *Waste Manag* 66:23–35. <https://doi.org/10.1016/j.wasman.2017.03.029>
52. Buckwell A, Nadeu E (2016) Nutrient recovery and reuse (NRR) in European agriculture. A review of the issues, opportunities, and actions. RISE Foundation, Brussels
53. George E (2020) Consultation about phosphorus flows in tangerine production with Prof. George, Director of Research at the Leibniz Institute of Vegetable and Ornamental Crops (IGZ)
54. Golomb A, Goldschmidt EE (1987) Mineral nutrient balance and impairment of the nitrate-reducing system in alternate-bearing 'wiling' Mandarin trees. *J Am Soc Hortic Sci* 112:397–401
55. Bedoic R, Ćosić B, Duić N (2019) Technical potential and geographic distribution of agricultural residues, co-products and by-products in the European union. *Sci Total Environ* 686:568–579. <https://doi.org/10.1016/j.scitotenv.2019.05.219>

56. Zhang QH, Yang WN, Ngo HH et al (2016) Current status of urban wastewater treatment plants in China. *Environ Int* 92–93:11–22. <https://doi.org/10.1016/j.envint.2016.03.024>
57. Aramaki T, Thuy NTT (2010) Material flow analysis of nitrogen and phosphorus for regional nutrient management: case study in Haiphong, Vietnam. In: Sumi A, Fukushi K, Honda R, Hassan KM (eds) *Sustainability in food and water: an Asian perspective*. Springer, Netherlands, Dordrecht, pp 391–399
58. Pham HG, Harada H, Fujii S et al (2017) Transition of human and livestock waste management in rural Hanoi: a material flow analysis of nitrogen and phosphorus during 1980–2010. *J Mater Cycles Waste Manag* 19:827–839. <https://doi.org/10.1007/s10163-016-0484-1>
59. Schaffner M, Bader H-P, Scheidegger R (2011) Modeling non-point source pollution from rice farming in the Thachin river basin. *Environ Dev Sustain* 13:403–422. <https://doi.org/10.1007/s10668-010-9268-2>
60. Taizhou Statistical Bureau (2019) *Statistics yearbook 2019 of Taizhou city*. Taizhou
61. Vitousek PM, Aber JD, Howarth RW et al (1997) Human alteration of the global nitrogen cycle: sources and consequences. *Ecol Appl* 7:737–750. [https://doi.org/10.1890/1051-0761\(1997\)007\[0737:HAOTGN\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1997)007[0737:HAOTGN]2.0.CO;2)
62. de Boer MA, Wolzak L, Slootweg JC (2019) Phosphorus: reserves, production, and applications. In: Ohtake H, Tsuneda S (eds) *Phosphorus recovery and recycling*. Springer, Singapore, pp 75–100
63. Möller K (2015) Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. *Agron Sustain Dev* 35:1021–1041. <https://doi.org/10.1007/s13593-015-0284-3>
64. Wong JWC, Wang X, Selvam A (2017) Improving compost quality by controlling nitrogen loss during composting. In: Wong JWC, Tyagi RD, Pandey A (eds) *Current developments in biotechnology and bioengineering*. Elsevier, Amsterdam, pp 59–82
65. International Renewable Energy Agency (2017) *Biogas for domestic cooking—technology brief*. IRENA, Abu Dhabi
66. Garmendia-Lemus S, Moshkin E, Hung Y et al (2024) European farmers' perceptions and intentions to use bio-based fertilisers: insights from the theory of planned behaviour and perceived utility. *J Clean Prod* 434:139755. <https://doi.org/10.1016/j.jclepro.2023.139755>
67. Zhang Q, Xiao H, Duan M et al (2015) Farmers' attitudes towards the introduction of agri-environmental measures in agricultural infrastructure projects in China: evidence from Beijing and Changsha. *Land Use Policy* 49:92–103. <https://doi.org/10.1016/j.landusepol.2015.07.021>
68. Moshkin E, Garmendia Lemus S, Bamelis L, Buysse J (2023) Assessment of willingness-to-pay for bio-based fertilisers among farmers and agricultural advisors in the EU. *J Clean Prod* 414:137548. <https://doi.org/10.1016/j.jclepro.2023.137548>
69. Neset T-SS, Bader H-P, Scheidegger R (2006) Food consumption and nutrient flows: nitrogen in Sweden since the 1870s. *J Ind Ecol* 10:61–75. <https://doi.org/10.1162/jiec.2006.10.4.61>
70. Liu Y, Lyu Q, He S et al (2015) Prediction of nitrogen and phosphorus contents in citrus leaves based on hyperspectral imaging. *Int J Agric Biol Eng* 8:80–88
71. Menino MR, Carranca C, de Varennes A (2007) Distribution and remobilization of nitrogen in young non-bearing orange trees grown under mediterranean conditions. *J Plant Nutr* 30:1083–1096. <https://doi.org/10.1080/01904160701394543>
72. U.S. Department of Agriculture (2019) Search result for tangerines, (mandarin oranges), canned, juice pack. In: FoodData Cent. <https://fdc.nal.usda.gov/fdc-app.html#/food-details/169106/nutrients>. Accessed 15 Nov 2020
73. Czech A, Zarycka E, Yanovych D et al (2020) Mineral content of the pulp and peel of various citrus fruit cultivars. *Biol Trace Elem Res* 193:555–563. <https://doi.org/10.1007/s12011-019-01727-1>
74. U.S. Department of Agriculture (2019) Search result for tangerine peel. In: FoodData Cent. <https://fdc.nal.usda.gov/fdc-app.html#/food-details/444009/nutrients>. Accessed 15 Nov 2020
75. Soceanu A, Dobrinas S, Birghila S et al (2009) Levels of phosphorus in citrus fruits. *Ovidius Univ Ann Chem* 20:87
76. Liu Y, Shi J, Langrish TAG (2006) Water-based extraction of pectin from flavedo and albedo of orange peels. *Chem Eng J* 120:203–209. <https://doi.org/10.1016/j.cej.2006.02.015>
77. U.S. Department of Agriculture (2019) Search result for tangerine juice, raw. In: FoodData Cent. <https://fdc.nal.usda.gov/fdc-app.html#/food-details/169925/nutrients>. Accessed 15 Nov 2020
78. Yan N, Zhang Y-L, Xue H-M et al (2015) Changes in plant growth and photosynthetic performance of *Zizania latifolia* exposed to different phosphorus concentrations under hydroponic condition. *Photosynthetica* 53:630–635. <https://doi.org/10.1007/s11099-015-0149-7>
79. Dibar DT, Zhang K, Yuan S et al (2020) Ecological stoichiometric characteristics of Carbon (C), Nitrogen (N) and Phosphorus (P) in leaf, root, stem, and soil in four wetland plants communities in Shengjin Lake. *China PLOS ONE* 15:e0230089. <https://doi.org/10.1371/journal.pone.0230089>
80. Chen C, Wang F, Hong Y et al (2019) The biomass accumulation and nutrient storage of five plant species in an in-situ phytoremediation experiment in the Ningxia irrigation area. *Sci Rep* 9:11365. <https://doi.org/10.1038/s41598-019-47860-8>
81. U.S. Department of Agriculture (2019) Search result for wild rice, raw. In: FoodData Cent. <https://fdc.nal.usda.gov/fdc-app.html#/food-details/169726/nutrients>. Accessed 14 Nov 2020
82. Surendiran G, Alsaif M, Kapourchali FR, Moghadasian MH (2014) Nutritional constituents and health benefits of wild rice (*Zizania* spp.). *Nutr Rev* 72:227–236. <https://doi.org/10.1111/nure.12101>
83. Jain A, Singh HB, Bhattacharyya PR (2012) The ethnobotany and nutritional values of wild rice [*Zizania latifolia* (Griseb.) Turcz. ex Stapf] (Poaceae) in Manipur. NISCAIR-CSIR, New Delhi
84. Zhai CK, Lu CM, Zhang XQ et al (2001) Comparative study on nutritional value of Chinese and North American wild rice. *J Food Compos Anal* 14:371–382. <https://doi.org/10.1006/jfca.2000.0979>
85. U.S. National Center for Biotechnology Information (2020) PubChem Compound Summary for CID 1176, Urea. <https://pubchem.ncbi.nlm.nih.gov/compound/1176>. Accessed 16 Nov 2020
86. Roy RN, Food and Agriculture Organization of the United Nations (2006) *Plant nutrition for food security: a guide for integrated nutrient management*. Food and Agriculture Organization of the United Nations, Rome

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