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Phosphorus Utilization Efficiency and Status of Phosphorus Reuse in China from 1990 to 2019

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Abstract: Phosphorus (P) is an essential element for supporting our life and is a non-renewable resource. This study applied dynamic material flow analysis to elucidate the phosphorus flow characteristics in China over the period from 1990–2019. Based on this, we developed a P resource efficiency index system and further explored the potential reasons for the changes in different areas by analyzing the inflow, outflow, and reuse of P in various modules. Results show that the phosphorus utilization efficiency (PUE) in crop planting increased from 63% in 1990 to 72% in 2019, while this figure in feeding livestock increased from 35% in 1990 to 42% in 2019 due to the utilization of straw. The figure in aquaculture remained low at 9% in 2019. The total P amount used for human consumption increased to 2562 Gg in 2019 due to changes in dietary habits, and the overall P recycling rate (PRR) for various human activities jumped to 58% in 2019. Based upon these results, several policy suggestions are proposed from governance, technology, and economic instruments perspectives.

Keywords: phosphorus; phosphorus cycle model; phosphorus efficiency in use; circular use of resources; China

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Citation: Wu, Y.; Liu, J.; Geng, Y.; Wu, D. Phosphorus Utilization Efficiency and Status of Phosphorus Reuse in China from 1990 to 2019. *Agriculture* **2023**, *13*, 2262. https://doi.org/10.3390/agriculture13122262

Academic Editor: Ciro Antonio Rosolem

Received: 31 August 2023
Revised: 25 November 2023
Accepted: 1 December 2023
Published: 11 December 2023

1. Introduction

The global population is predicted to increase to 9.8 billion by 2050, leading to the global food demand doubling [1–3]. In order to respond to such food security challenges, it is urgent to increase agricultural production [4]. Fertilization is a key factor in developing modern agriculture and increasing food production [5], which induces large-scale mining of phosphate ore [6].

Phosphorus is an essential and indispensable element for human metabolism [7,8]. Over 80% of phosphate is used in making fertilizer to increase crop yields [9]. In recent years, the extensive exploitation of phosphorus resources has induced concerns regarding its depletion and potential food security issues [10]. Several countries, such as China, have claimed phosphorus as a strategic resource [11,12]. In order to address this issue, it is necessary to promote the circular economy in the agricultural sector, such as through the reduction, reuse, and recycling of phosphorus resources [13].

China is the world's largest producer and consumer of P fertilizer [14]. The confirmed phosphate rock reserves in China reached 3.2 billion tonnes in 2019, accounting for 4.5% of the global total, with 95 million tonnes of domestic production contributing to 42% of the global phosphate rock mining [15]. Meanwhile, rapid economic development has greatly improved the life quality of Chinese people, which, in turn, has resulted in increasing demand for P and corresponding eutrophication concerns caused by excessive use of fertilizer [16–18]. Consequently, it is critical to assess the overall P resource efficiency in China so that efficient utilization and management of P resources can be achieved.

Material flow analysis (MFA) is an analytical method for systematically evaluating specific material flows and inventories with explicit constraints on system boundaries and periods [19,20]. Many studies have applied this approach to analyze the flow characteristics of specific elements, such as tungsten [21], nickel [22], and other mineral resources such as graphite [23]. MFA results can help provide insights to improve the overall resource efficiency. In terms of phosphorus utilization efficiency (PUE), relevant studies can be roughly categorized into two groups. In the first, PUE is calculated using the ratio of output P to input P of each phosphorus-related module at different scales obtained from the P material flow model [24–30]. For example, Wu et al. [28] measured the PUE of each subsystem in China's agricultural system from 1980 to 2012. In addition, Jiang and Yuan [29] assessed PUE for chemical production, crop planting, agricultural product processing, and livestock and poultry breeding in the Chaohu Lake basin from 1978 to 2012. Chowdhury and Zhang [25] evaluated the P efficiency in 20 countries based on the results of the current material flow literature. Chen and Graedel [24] selected phosphate mining, chemical production, crop planting, and social consumption modules for PUE analysis for the period of 1961–2013 based on the global P material flows. In addition, several studies focus on PUE for specific modules, such as the crop production module [28,30] and agricultural product processing module [27]. Another relevant research group focuses on field experiments to compare the effects of different methods on PUE for a particular type of crop or a specific fertilization method, such as irrigation [31,32].

Phosphorus recycling contributes to environmental protection, waste management, food security, social equity, and social value enhancement [33]. Ma et al. [34] found that 47% of phosphorus inflow was from waste management of agricultural planting modules for organic fertilizers in China from 1984 to 2008. Antikainen et al. [35] found that phosphorus recycling contributed significantly to the total phosphorus inflow in Finland, accounting for about 50% of the total input, with livestock and poultry manure entering agricultural planting modules making up 48% from 1995 to 1999. Two other relevant studies concluded that human excreta accounted for less than 10% of the total phosphorus inflow when integrating recycled phosphorous into agricultural planting modules [36,37]. Furthermore, legacy P in agricultural land plays a special role in enhancing the effectiveness of fertilizers [38]. Typically, crops absorb P from the soil to support their growth, part of which is removed from the soil along with the harvested crops. There are also natural flow processes like runoff that remove phosphorus from the soil. Therefore, accurately determining and maintaining soil P balance is critical for P management [39].

This study aims to investigate the dynamic features of phosphorus flows and measure phosphorus use efficiency (PUE) and resource reuse in China for the period from 1990–2019 by employing dynamic material flow analysis and a P resource efficiency index system, with a focus on overall human activity in China and the phosphorus resource efficiency across various fields. Upon further analysis of the underlying causes for changes in phosphorus resource efficiency in different areas, we can make recommendations for improved phosphorus resource utilization. This study, in comparison to others, uses an adjusted model of China's P resource cycle as its data foundation, covering the entire process from P mining to recycling on a macro scale. Using the constructed resource efficiency indicator system, we analyzed P resource efficiency in different modules. The results show a broader coverage.

2. Materials and Methods

2.1. System Boundary

The system boundary of this study is shown in Figure 1. It is divided into five phases: ore extraction, P chemical manufacturing, agricultural production, human consumption, and waste management. Agricultural production includes crop production, agricultural processing, livestock farming, aquaculture, and food processing. P flows are released into the local environment (inland water, ocean, atmosphere, and cultivated and non-arable land) and embodied in the international trade. P is recycled through livestock manure, straw, human manure, wastewater, and other solid wastes, and retained in soil. This study employs data spanning from 1949 to 2019, but the scope of phosphorus resource efficiency analysis is restricted to mainland China from 1990 to 2019, due to the earlier developmental status and data quality of China. The major calculations were performed using R (version 4.1.1).

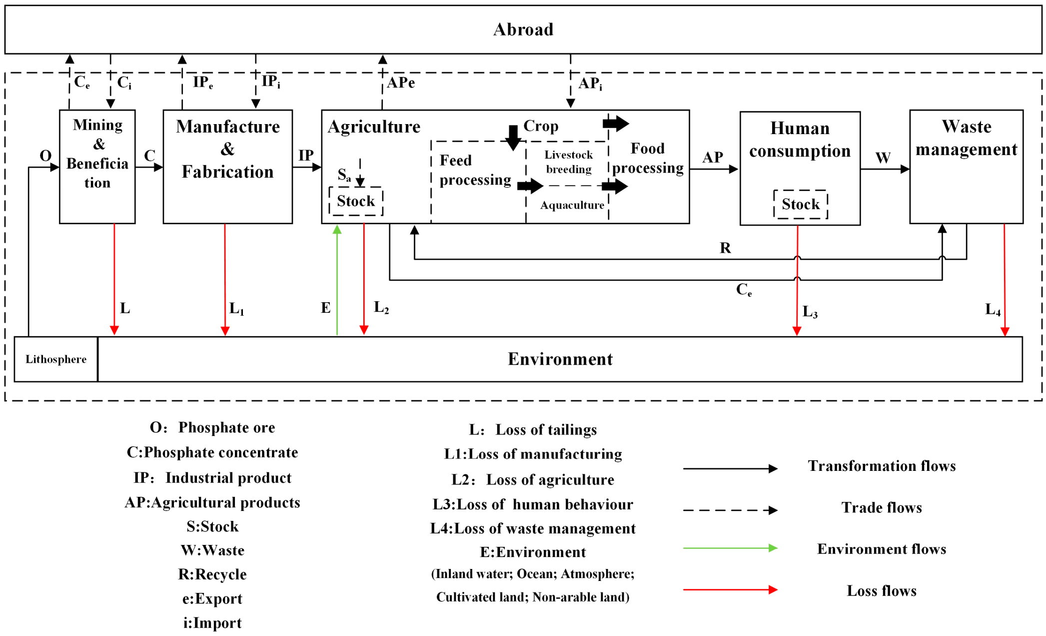


Figure 1. System boundary of the P flows in China.

2.2. *Phosphorus Cycle Model*

This study adopts the P cycle model established by Liu et al. [40]. We adjusted the calculation of P emission in the aquaculture module (Supplementary Materials Figure S1) and updated the results to 2019. The model covers 14 modules, including natural activities and human activities, as well as 102 P flows. The calculation of the model is based on the law of conservation of matter. Each flow is calculated using the general material flow method, which is broadly divided into three categories: (1) independent calculation, (2) non-independent calculation, and (3) system balance.

2.3. *Efficiency of Phosphorus Resource Utilization*

2.3.1. Phosphorus Utilization Efficiency (PUE)

The P utilization efficiency index system is based on the results of the P cycle model, aiming to achieve the purpose of assessing the P efficiency of each module by analyzing the results of P input and output in the modules. 'The core of constructing the indicator system lies in considering the proportion of total inflows and outflows for the set objectives [24–29]. Generally, the utilization of P in various modules varies significantly. It is essential to determine the real efficiency of P in the key utilization modules. The P utilization efficiency of the following four modules was mainly analyzed: PUE of livestock and poultry breeding, agricultural product processing, agricultural planting, and aquaculture modules.

$$\mathrm{PUE}_{\text{Livestock breeding}} = \frac{\mathrm{Outflow}_{\mathrm{LB}}}{\mathrm{Inflow}_{\mathrm{LB}}} \times 100 = \frac{\text{Livestock\&poultry} + \text{Eggs\&Dairy}}{\text{Feed} + \text{Pasture}} \times 100 \quad (1)$$

The P outflows from the livestock breeding module include farrowing livestock for eggs and dairy and the net export of livestock and poultry products. The inflow includes feed and pasture (Equation (1)).

$$\mathrm{PUE}_{\text{Agro-processing system}} = \frac{\mathrm{Outflow}_{\mathrm{APS}}}{\mathrm{Inflow}_{\mathrm{APS}}} \times 100 = \frac{\text{Food} + \text{Nonfood} + \text{Feed}}{\text{Aquatic product} + \text{L\&P} + \text{Straw} + \text{Feed additives}} \times 100 \quad (2)$$

The P outflows of the agricultural product processing module include food, non-food, feed, non-food net exports, and feed net exports. The agro-processing module P inflow includes farmed aquatic products, livestock and poultry farming, crops, straw, feed additives, wood, natural freshwater products, and natural seawater products (Equation (2)).

$$\mathrm{PUE}_{\text{Agricultural cultivation}} = \frac{\mathrm{Outflow}_{\mathrm{AC}}}{\mathrm{Inflow}_{\mathrm{AC}}} \times 100 = \frac{\text{Crop} + \text{Straw}}{\text{Atmospheric deposition} + \text{Weathering} + \text{Fertilizer\&Pestic} + \text{Manure\&Compost}} \times 100 \quad (3)$$

The outflows of the agricultural planting module comprise crops and net crop exports and exclude straws. The inflows include atmospheric deposition, weathering, fertilizers, pesticides, sludge manure, and compost (Equation (3)).

$$\mathrm{PUE}_{\text{Aquaculture}} = \frac{\mathrm{Outflow}_{\text{Aquaculture}}}{\mathrm{Inflow}_{\text{Aquaculture}}} \times 100 = \frac{\text{Aquatic product}}{\text{Feed}} \times 100 \quad (4)$$

The inflows of the aquaculture module include farmed aquatic products and net exports of aquatic products.

In addition to evaluating PUE, we also utilized two indicators, namely P recycling rate (PRR) and proportion of using recycled P (PURP), to measure the P recovery in the module, with PRR representing the proportion of total recycled P to the total P waste. We complement this index system by extending the analysis into waste sector and municipal sector.

2.3.2. Phosphorus Recycling Rate

The phosphorus recycling rate (PRR) refers to the proportion between the total amount of recycled P and the total amount of waste P in a certain system.

$$\mathrm{PRR}_{\mathrm{SAF}} = \frac{\text{Total recycling}_{\text{straw}}}{\text{Total waste}_{\text{straw}}} \times 100 \quad (5)$$

The recycling rate of the recycled P in the process of using straws as fertilizers is shown above (Equation (5)).

$$\mathrm{PRR}_{\mathrm{HA}} = \frac{\text{Total recycling}_{\mathrm{HA}}}{\text{Total waste}_{\mathrm{HA}}} \times 100 = \frac{\text{Manure} + \text{faeces} + \text{sludge} + \text{Compost} + \text{straw}}{\text{Total waste}} \times 100 \quad (6)$$

The recycling rate of the recycled P in human activities is shown above (Equation (6)).

2.3.3. Proportion of Recycled P Use

By calculating the proportion of recycled P to the total P inflow in the module, a clearer understanding of the reused P input in the agricultural divisions can be obtained. The proportion of recycled P used refers to the proportion between the total amount of recycled P used and the total amount of P inflow in a certain system.

$$\mathrm{PURP}_{\mathrm{AP}} = \frac{\text{Total amount of using recycled }\mathrm{P}_{\mathrm{AP}}}{\mathrm{P}_{\text{ inflow AP}}} \times 100 = \frac{\text{Manure} + \text{Faeces} + \text{Sludge} + \text{Compost} + \text{straw}}{\text{Pinflow}} \times 100 \quad (7)$$

The proportion of recycled P used in agricultural planting is shown above (Equation (7)).

$$\mathrm{PURP}_{\mathrm{A\&LB}} = \frac{\text{Total amount of using recycled }\mathrm{P}_{\mathrm{A\&LB}}}{\mathrm{P}_{\text{inflow A\&LB}}} \times 100 = \frac{\text{Feed} + \text{Agricultural product processing crop residual}}{\text{Pasture} + \text{Feed}} \times 100 \quad (8)$$

The proportion of recycled P used in aquaculture and livestock breeding is shown above (Equation (8)).

2.4. Data Sources

The data utilized in this study were divided into two categories, namely activity data and parametric data (refer to Supplementary Materials). The same data sources used by Liu et al. [40] were employed for activity data in order to ensure model coherence. With regard to parametric data, updates were made in conjunction with newly available data from statistical yearbooks at the national level and academic literature pertaining to recent years (please refer to Supplementary Materials Section S1 for details).

2.5. Uncertainty Analysis

Uncertainty analysis is performed using the Monte Carlo simulation method for activity data, other parameters, and the final P flow results. A uniform distribution was used for all the activity data, and 0.1 was chosen as the coefficient of variation (CV). Uniform and triangular distributions were used for all the parametric data, depending on the properties of the parametric data, and 0.1 to 0.3 was chosen as the CV, depending on the reliability of the parametric data source. The results of the uncertainty analysis are shown in Supplementary Materials Figure S4, indicating that the uncertainty of the various parameters used in this study had only a marginal effect on our main findings.

3. Results and Discussion

3.1. Overall P Resource Efficiency

Our research revealed that, up to 2019, there has been a substantial transformation in the characteristics of P material flow in China, indicating a discernible evolution in its management and utilization. Figure 2 presents the P material flow for China in 2012 and 2019. Based on the results, it can be observed that the inflow of chemical fertilizers has decreased, while the output of crops has remained relatively stable, with only a slight increase from 4052 Gg in 2012 to 4392 Gg in 2019. Additionally, the P outflow from livestock and poultry farming has also decreased, from 814 Gg in 2012 to 612 Gg. Concurrently, there has been an increase in the P content in agricultural products within the human consumption cycle. The demand for aquatic products has risen, but the P outflow from human consumption waste entering the natural environment has declined. There is an increase in P outflow into waste management, accompanied by a rise in P recycled back to agriculture after waste processing. This indicates that China's utilization of P resources in 2019, compared to previous years, is moving towards a more sustainable direction. The P resource efficiency index system reveals that most indicators have been increasing since 1990, including the PUE in agricultural planting and agricultural product processing modules, PURP in agricultural planting and livestock and poultry breeding modules, PRR in straw, and the PRR of human activities as a whole. However, PUE in aquaculture and livestock breeding modules decreased or changed slightly.

3.2. P Mining and Chemical Production

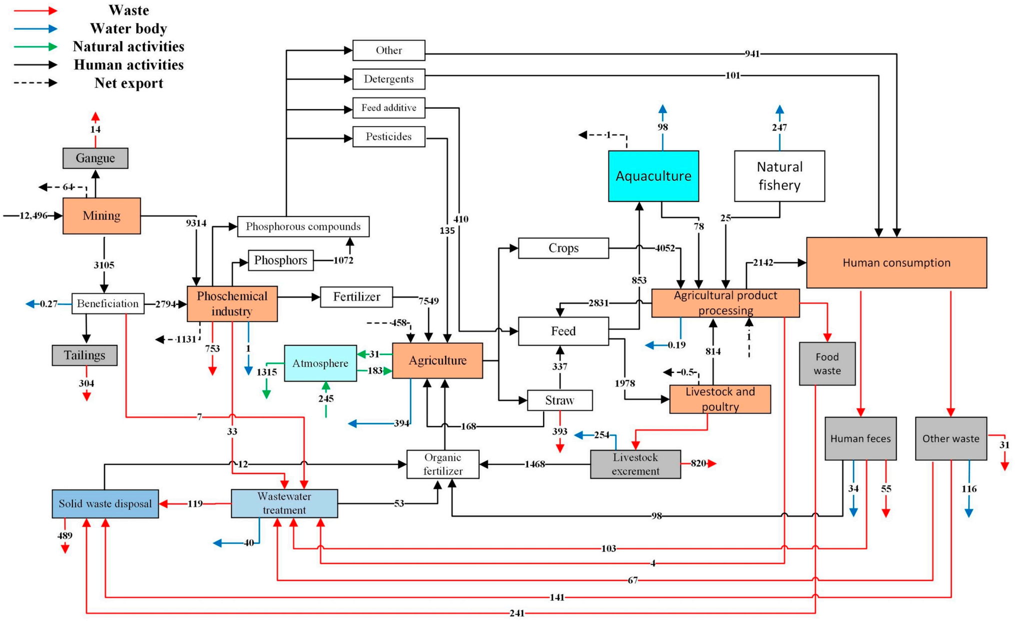
3.2.1. P Mining

China's phosphorus ore mining reached its historical highest point in 2016, with a total P outflow of 24,967 Gg. Since then, the Chinese government has implemented stricter control measures and environmental protection policies for mineral resources, leading to a continuous decrease of P outflow from mines, reaching 16,135 Gg in 2019 [12]. During this period, the outflow of P from mineral exploitation and the P chemical industry has shown a significant downward trend.

The decline in phosphate ore grade has posed a challenge to sustainable development and utilization of phosphate resources, making P mining more difficult. This has been concentrated in a few companies, with Yuntianhua* in Yunnan province, Wengfu* in Guizhou province, and the Kai Phosphorus Group* in Guizhou province accounting for 70% of China's total production [41]. Guizhou province has implemented "planning production by slag amount", driving enterprises to determine production based on the amount of phosphogypsum produced in the current year, leading to a 24% increase in the comprehensive utilization rate of phosphogypsum resources in 2018 [42]. However, challenges remain in terms of low profit and recognition, as well as high freight costs associated with phosphogypsum products. Additionally, rapid development of new energy vehicles has intensified the demand for high-grade phosphate rock.

* YUNTIANHUA Group, Kunming, Yunnan, China; WENGFU Group, Guiyang, Guizhou, China; KAI Phosphorus Group, Guiyang, Guizhou, China.

(a) 2012 P– flow Gg



(b) 2019 P– flow Gg

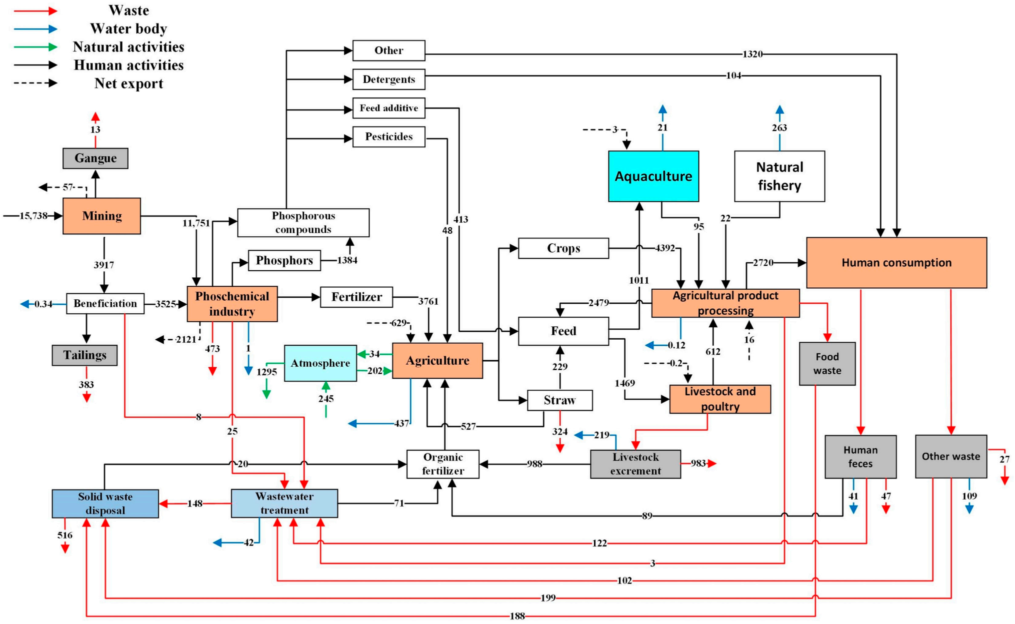


Figure 2. The overall framework of the P cycle model in China in 2012 (**a**) and 2019 (**b**).

3.2.2. Phosphate Chemical Industry

In 2012, an unusual fluctuation was observed in the output of phosphate fertilizer, which deviated from the phosphate outflow rule of phosphate mining. However, since 2016, the phosphate outflow of the phosphate chemical module has gradually decreased and reached 6947 Gg in 2019.

Since 2002, the second largest P outflow from chemical production, used as a P additive for feed, has remained between 8% and 9% of the total P outflow from this module. This peaked in 2013 at 794 Gg and dropped to 629 Gg in 2019. Pesticides, the third largest P output product from chemical production, accounted for about 2% of the chemical module since 2005, peaking at 267 Gg in 2014 and dropping to 151 Gg in 2019. Detergents, the fourth largest P output product, accounted for less than 2% since 2015, with a flow of 123 Gg in 2019. Since 2011, the proportion of P outflow from yellow P has been less than 0.5%, dropping to 0.15% in 2019, with a flow of 10 Gg.

3.3. Agricultural Planting

3.3.1. Crop Cultivation

In crop cultivation, the peak value of the P inflow appeared in 2012, reaching 9724 Gg; then, it began to decline to 5417 Gg in 2019. The bulk came from phosphate fertilizer, which reached 7549 Gg in 2012 and gradually decreased to 3761 Gg in 2019. The inflow of P in the agricultural planting module mainly depends on phosphate fertilizer, and the yield of phosphate fertilizer is the key factor affecting the change in P in agricultural planting soil. The change in the soil P inventory in recent years is shown in Supplementary Materials Figure S2. The inflow of P from straw returning to the field has gradually increased in recent years, from 168 Gg in 2012 to 527 Gg in 2019. This increase reflects that the Chinese government has strengthened the utilization of straw returning to fields [43]. However, straw has yet to be fully utilized. Approximately 20% of straw has not been reused in China [44]. The P outflow from agricultural planting has remained stable in recent years. There was a slight increase from 4636 Gg in 2012 to 4698 Gg in 2019 (Figure 2). Most outflows come from agricultural planting and flow to the agricultural product processing module, which also maintains a steady upward trend, rising from 3755 Gg in 2012 to 4163 Gg in 2019. The total amount of P flowing into freshwater from agricultural planting remained relatively stable annually, increasing from 352 Gg in 2012 to 393 Gg in 2019. With the gradual decline in phosphate fertilizer inputs, China's agricultural planting has also developed in a more sustainable direction. However, there was no significant decline in P flowing from the agricultural planting module to freshwater, indicating that the risk of eutrophication in water bodies was not mitigated.

3.3.2. PUE in Agriculture

Regarding the PUE of agricultural planting, there was an obvious fluctuation in the utilization efficiency of P resources, beginning with a value of 63% in 1990, oscillating around 45% in the intervening period. This figure has gradually increased since 2015 and reached 72% in 2019. Based on the calculations, the P outflow exhibited a persistent and incremental rise since 1990, with slight fluctuations. The variations in PUE can be attributed to the fluctuation in P inflow, mainly the fertilizer P. This has decreased since 1990 due to stricter management measures and more environmentally friendly fertilizer usage policies [43]. This has led to a reduction in P fertilizer production and an increase in straw returned to the field, which has improved the overall P utilization and recovery efficiency in agricultural cultivation.

Agricultural P inputs (Table 1), such as phosphate fertilizer and pesticide, reached a peak of 7684 Gg in 2012. However, crop utilization efficiency of P declined to its lowest point of 37% in 2012, indicating that excessive inputs did not lead to a significant increase in crop yields. Since 2015, grain output has steadily remained at 650 million tonnes [2]. In response, the Action Plan for Zero Growth in Chemical Fertilizer Usage was implemented, resulting in a decrease in agricultural chemical fertilizer output and an increased PUE from agricultural planting. The value of PUE increased from 38% in 2012 to 72% in 2019.

Table 1. PUE of agricultural planting.

Year	Output (P-Gg)						Input (P-Gg)									PUE (%)
	Crop		Straw		Exports	Total	Atmospheric Deposition	Weathering	Fertilizer & Pesticide		Manure & Compost				Total	
1990	2255	141	392	188	(40)	2937	99	69	2263	18	1120	183	3	4	3759	63
2012	3715	337	224	393	(458)	4211	183	64	7549	135	1468	98	53	12	9562	38
2019	4163	229	139	324	(629)	4226	202	71	3761	48	988	89	71	20	5250	72

3.3.3. Resource Reuse

The PURP in agricultural planting increased from 19% in 2012 to 32% in 2019 (Table 2), while the PRR in straws as fertilizers rose from 15% in 2012 to 43% in 2019. The substantial increase in returned straw made the greatest contribution to improving the resource efficiency of this module, while the P in crop residues used as feed through processing remained stable, although with a slight increase. The total P input decreased from 9724 Gg in 2012 to 5417 Gg in 2019, which is the primary reason for the increase in PRR.

Table 2. Proportion of using recycled P from agricultural planting.

Year	**Total Recycle (P-Gg)**						**Total Input (P-Gg)**	**P Recycling Rate (%)**
	Subsystem					**Total**		
	L & P	**Human Consumption**	**Wastewater Treatment**	**Solid Waste Treatment**	**Agriculture**		**Total**	
	Manure	**Feces**	**Sludge**	**Compost**	**Straw**			
2012	1468	98	53	12	168	1799	9724	19
2019	988	115	63	19	527	1712	5417	32

The agricultural P input increased from 337 Gg in 2012 to 527 Gg in 2019. This increase was due to the sharp decline in the use of chemical phosphate fertilizer and the steady increase in P recovered from other systems, including returned straw, composting, sludge, and human excreta. The proportion of straw reused as feed decreased from 337 Gg in 2012 to 229 Gg in 2019, representing a decrease of 32% (Table 3).

Table 3. P recycling rate in straws as fertilizers.

Year	**Total Recycle (P-Gg)**			**Total Waste (P-Gg)**				**P Recycling Rate (%)**
	Subsystem	**Methods**	**Destination**	**Methods**			**Total**	
	Agriculture	**Straw**	**Agriculture**		**Straw**			
2012		168		337	224	393	1122	15
2019		527		229	139	324	1219	43

3.3.4. Soil P Balance

Based on the approach of Haygarth et al. [45] in studying P balance, this study delineates the P flows entering arable and non-arable land (Figure 3) and the P outflows from arable land, illustrating the state of China’s soil P balance since 1990. The peak of soil P accumulation in agricultural planting occurred in 2012, reaching 5088.1 Gg, and then showed a declining trend, especially after the adjustment of China’s P resource management policy in 2016, leading to a significant decrease. By 2019, it dropped to 719 Gg. The reason is that the significant reduction in P fertilizer inputs did not affect crop yields, indicating that, since 2016, P utilization in China’s agricultural planting has become more effective, thus reasonably improving the soil P balance. If the regional soil P balance has been achieved, then in the fertilization of the following year, there is no need to apply more than the P outflow of the previous year [39]. The P inputs into non-arable land mainly come from tailings in the P mining stage, solid waste in the chemical production stage, crop straw, animal manure, and human domestic waste.

3.4. Livestock and Aquaculture

3.4.1. Livestock P Utilization

Pasture and feed are the primary sources of P inflow for the livestock and poultry breeding module. The P inflow from pasture sources decreased slightly from 2023 Gg in 2012 to 1469 Gg in 2019. Simultaneously, the overall P outflow of the module decreased from 3356 Gg in 2012 to 2803 Gg in 2019. This reduction was mainly due to a decrease in the outflow from the module to agricultural planting through excreta (from 1468 Gg in 2012 to 988 Gg in 2019). Additionally, the outflow of the module to agricultural product processing and freshwater also decreased from 814 Gg in 2012 to 612 Gg in 2019 and from 735 Gg in 2012 to 637 Gg in 2019, respectively. Factors such as African swine fever, fluctuations of pork prices, and the cyclical nature of pig breeding have impacted the investment in pig breeding and ultimately influenced the stock of pigs.

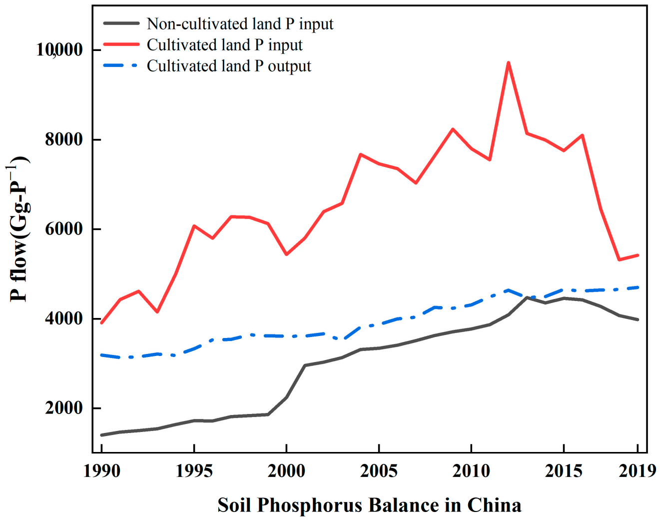
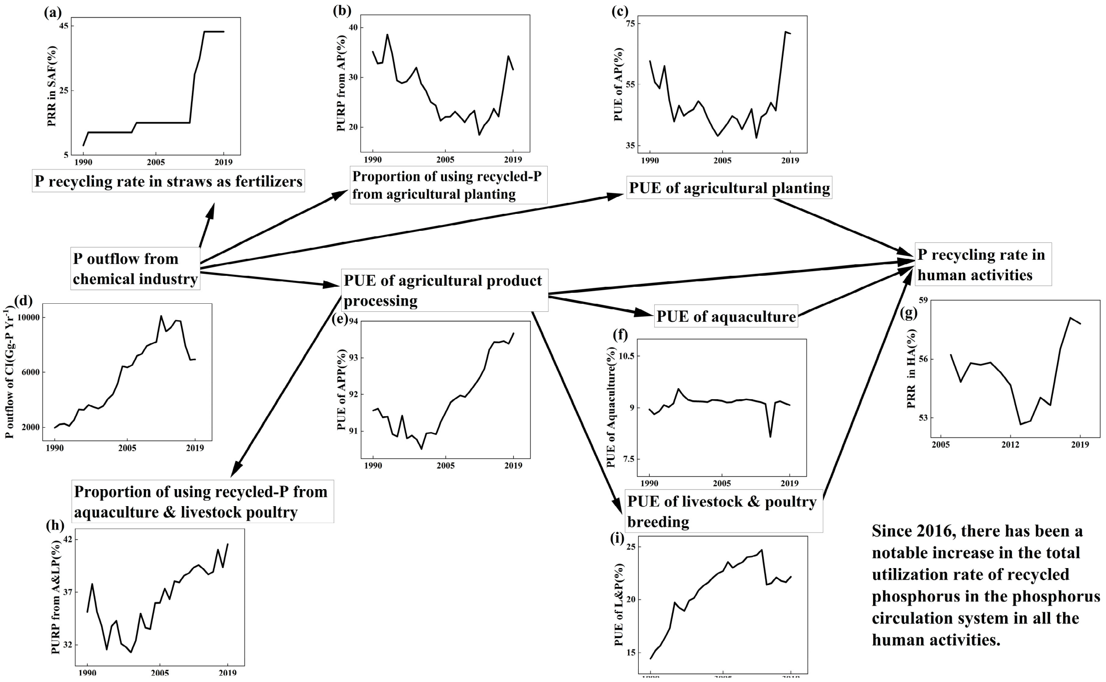


Figure 3. Soil P balance in China.

According to our results (Figure 4), the P inflows and outflows from livestock and poultry breeding have declined in the past two years. In 2012, more extensive concentrated animal feeding operations accounted for approximately 80% of chickens, 60% of pigs, and 40% of dairy cattle in China [46]. However, there is a common problem of excessive P usage in breeding. Due to poor management, a large amount of P in excreta has become one of the leading causes of water eutrophication [47]. Recently, livestock droppings returning to fields have experienced dynamic changes due to the government's livestock breeding management, such as the reuse of droppings. To further reduce P emission, we should enable farmers to access advanced technologies so that they can improve their behaviors.



Since 2016, there has been a notable increase in the total utilization rate of recycled phosphorus in the phosphorus circulation system in all the human activities.

Figure 4. Dynamics of phosphorus resource reuse in China during the period of 1990–2019. (**a**) P recycling rate in straws as fertilizers; (**b**) Proportion of using recycled P from agricultural planting;

(**c**) PUE of agricultural planting; (**d**) P outflow from chemical industry; (**e**) PUE of agricultural product processing; (**f**) PUE of aquaculture; (**g**) P recycling rate in human activities; (**h**) Proportion of using recycled P from aquaculture & livestock poultry; (**i**) PUE of livestock & poultry breeding.

In terms of P resource utilization efficiency, an overall upward trend is observed, with PUE increasing from 14% in 1990 to 22% in 2019 (Table 4). This is attributed to the Chinese government's strengthening of fertilizer use management and the increasing technology advancement of poultry production, such as large-scaling and intensification of breeding [48]. Despite this, China still lags behind the most developed agricultural countries in terms of the utilization of P resources. [49,50].

Table 4. PUE of livestock & poultry breeding.

Year	**Output (P-Gg)**				**Input (P-Gg)**		**PUE (%)**
	Livestock & Poultry	**Eggs & Dairy**	**L&P Exports**	**Total**	**Feed**	**Pasture**	
1990	248	16	0.00	264	932	902	14
2012	739	75	0.46	814	1978	1382	24%
2019	535	78	(0.24)	612	1469	1293	22%

3.4.2. Aquaculture P Utilization

We modified the calculation methods for measuring aquaculture P utilization. Modifications were made to the inflow and outflow of P into freshwater and seawater, as part of the aquaculture module, resulting in significant deviations from the model proposed by Liu et al. [40] (see the Supplementary Materials Section S2). The findings indicate a progressive escalation in the discharge of P from the aquaculture system into freshwater, with values increasing from 47 Gg in 2007 to 60 Gg in 2017. Further methodological details are presented in the corresponding section.

The primary emission sources were Hubei Province, Guangdong Province, Jiangsu Province, Anhui Province, Zhejiang Province, the Guangxi Zhuang Autonomous Region, and Fujian Province. P from aquaculture flowing into seawater also increased gradually from 35 Gg in 2007 to 53 Gg in 2017. The increasing P outflow from aquaculture can be explained by the fact that Chinese fishery aquaculture farmers have widely adopted high-density and high-input aquaculture methods for high economic benefits, which pollutes the aquaculture environment with P caused by feed and fish excrement [51]. Moreover, the outflow of P from the aquaculture module to agricultural product processing continued to increase from 78 Gg in 2012 to 95 Gg in 2019. This study is limited by the inability to obtain the amounts of aquaculture products produced under different aquaculture methods, resulting in the utilization of an average value of emission factors. Further research is necessary to acquire more precise data so that the P emission can be calculated more accurately.

In terms of the estimated P flow rate from aquaculture into water bodies, the results show a decreasing trend. Other research findings suggest that only 5% to 40% of the nutrients of aquaculture feed are absorbed, while 80% of P often appears in sludge at the bottom of ponds [52]. Throughout the period from 1990–2019, the PUE of the aquaculture modules remained approximately 9% (Table 5). Although the aquaculture yield has increased in recent years, it has also been accompanied by an increase in P inflow. In 1990, a total input of 131 Gg was matched with a total output of 12 Gg. By 2019, the total input had risen to 1011 Gg, against a total output of 92 Gg. Thus, the utilization efficiency of aquaculture in China decreased. But P pollution remains a pressing issue due to the increased adoption of high-density and high-input aquaculture methods [53]. Relevant departments need to make further efforts to improve fishery PUE in order to reduce the risk of eutrophication.

Table 5. PUE of aquaculture.

Year	Output (P-Gg)			Input (P-Gg)	PUE (%)
	Aquatic Products (Artificially Cultured)	Aquatic Products Exports	Total	Feed	
1990	12	0	12	131	9
2012	78	0.63	78	853	9
2019	95	−3.15	92	1011	9

3.4.3. Resource Reuse

Agricultural breeding is essential for agricultural product processing modules, including livestock breeding and aquaculture, providing a considerable amount of P input. The PURP in agricultural breeding and aquaculture had increased from 31% in 2000 to nearly 42% in 2019 (Table 6). This is mainly attributed to the gradual rise in the proportion of crop residues used as feed in agricultural product processing, resulting in an increased P input from 846 Gg in 2000 to 1339 Gg in 2019. At the same time, the P inflow from pastures slightly decreased (Figure 5).

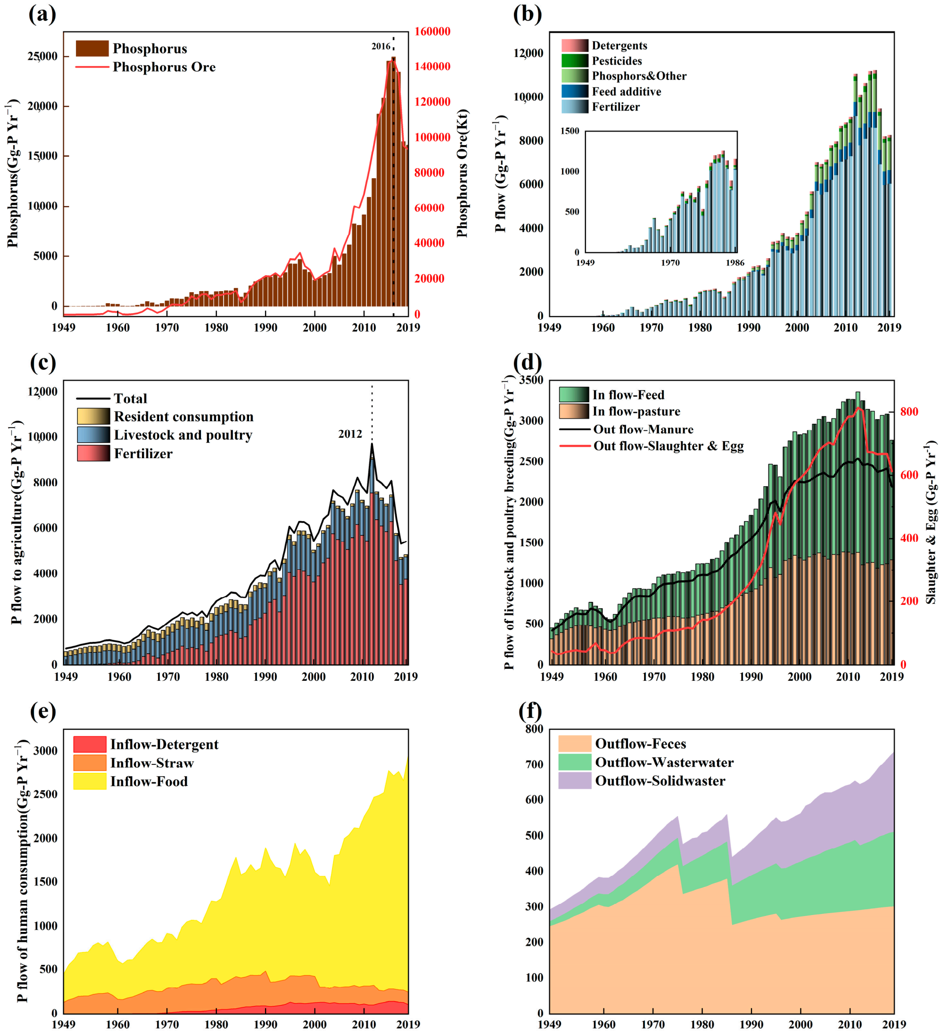


Figure 5. Dynamic characteristics of phosphorus resources in China, 1949–2019. (**a**) Phosphorus ore mining volume and phosphorus outflow; (**b**) phosphorus outflow from chemical products; (**c**) phosphorus inflow to agricultural planting; (**d**) phosphorus flow characteristics of livestock and poultry breeding; (**e**,**f**) phosphorus flow characteristics of human consumption.

Table 6. Proportion of using recycled P from aquaculture & livestock poultry.

Year	Total Recycle (P-Gg)			Total Input (P-Gg)			Recycled-P Using Rate (%)
	Agriculture (Straw)	Agricultural Product Processing-Crop Residual		Non-Arable Land	Agricultural Product Processing		
	Feed	Feed	Total	Pasture	Feed	Total	
2000	213	846	1059	1316	1955	3271	32
2012	337	1321	1658	1382	2831	4213	39
2019	229	1339	1568	1293	2479	3773	42

3.5. Overall Human Activity

3.5.1. Agricultural Product Processing

The PUE in agricultural product processing, as displayed in Figure 6, takes into account the P inflows from all relevant modules in the material flow calculation into agricultural processed products, including aquatic products, livestock and poultry, crops, straws, food additives, wood, and natural aquatic products. Concerning outflows, the outflows of P from processed products such as food, non-food, feed, and net exports are considered. The PUE in food processing remained stable at a high level, with an average of over 90% from 1990 to 2019.

3.5.2. Human Consumption

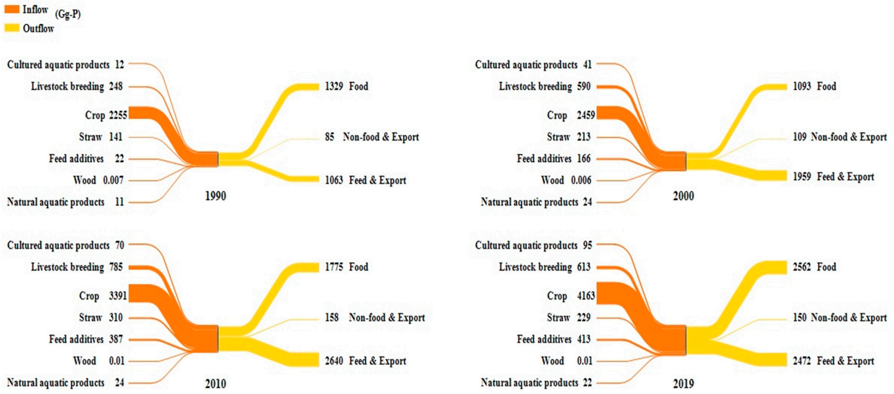
The output of artificially cultured aquatic products had significantly increased from 2012 to 2019, leading to an apparent upward trend in the P flowing into human consumption, from 1965 Gg in 2012 to 2562 Gg in 2019. Specifically, the output of freshwater products increased from 26,445 kt in 2012 to 30,137 kt in 2019, while the output of seawater products rose from 16,438 kt to 20653 kt during the same period [2]. This increase has been caused by improved living standards and increased demand for aquatic products [54]. Secondly, pork output was stable from 2012 to 2018, but suffered a significant decline in 2019, with an output of 42,553 kt (a 21% decrease from 54,037 kt in 2018) [2]. This drop was caused by African swine fever and blind demolition and construction in various Chinese regions, resulting in higher pork prices that impacted residents' lives [55]. Mutton and poultry production continued to rise, while beef production remained stable. Thirdly, the output of egg products increased from 28,612 kt in 2012 to 33,090 kt in 2019 [2], demonstrating a gradual upward trend. Egg consumption in China, the world's largest egg producer, has experienced a gradual upward trend due to government initiatives such as the inclusion of egg product processing projects in the Twelve Five-Year Plan and Thirteenth Five-Year Plan [56,57], as well as the move towards single-product deep processing, which has added to the value of eggs [48]. These measures have contributed to rapid development of the egg products industry and increased egg consumption in China. Lastly, China has placed a priority on food security, leading to a stable trend in food crop production. In addition, the reuse of compost, sludge from wastewater treatment, and solid waste treatment has also increased since 2012, with inflows of 115 Gg, 63 Gg, and 19 Gg, respectively in 2019, representing increasing rates of 17.4%, 17.3%, and 68%.

3.6. Phosphate Ore Trade Perspectives

China is the world's leading supplier of phosphate ore, with South Korea and Japan being its main export trading partners. China exported 297 kt of phosphate ore to South Korea, 214 kt to Japan, and 144 kt to the Philippines in 1995. In 2000, these numbers increased to 655 kt to South Korea and 146 kt to Japan. Although China listed P as a strategic resource in 2016, the trade in phosphate ore between China and South Korea remained relatively stable, with China exporting 276 kt of P to South Korea in 2019. Conversely, the amount of phosphate ore exported to Japan decreased significantly to 48 kt in 2019. China mainly imported phosphate ore from Morocco, reaching 114 kt in 2019 and accounting for 99% of its total imports.

(a) PUE of livestock & Poultry breeding

(b) PUE of Agricultural product processing



(c) PUE of Agricultural planting

(d) PUE of Aquaculture

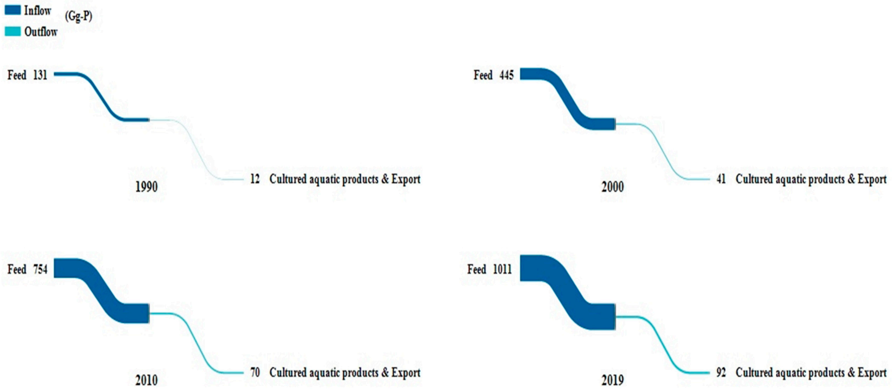


Figure 6. PUE of China in 1990, 2000, 2010, and 2019. (**a**) Livestock breeding; (**b**) agricultural product processing; (**c**) agriculture; (**d**) aquaculture.

In 1995, China mainly exported 659 kt of P chemical products with a total value of 269 million US dollars to Japan, Myanmar, Pakistan, and other countries. In 2010, China exported 8730 tonnes to India, Brazil, Vietnam, and other countries with a total value of 4.4 billion US dollars. In 2019, the export volume and value jumped to 13,785 kt and 7 billion US dollars, respectively, with India, Pakistan, and Vietnam as the major trade partners. Regarding import, in 1995, China imported 7446 kt of P chemical products with a total value of 1.8 billion US dollars from the US, Russia, Kazakhstan, and other countries. In 2010, the import volume and value dropped to 2101 kt and 1.8 billion US dollars, respectively, with Russia, the US, and Norway as the major trade partners. In 2019, the import volume and value rose to 2156 kt and 2.7 billion US dollars, respectively, mainly from Norway, Belgium, and Russia. Due to its advantageous geographical location and trade capabilities, Hong Kong has become a primary transit port for China's P chemical products, particularly with European countries and the United States.

3.7. Policy Implications

This study provides valuable information on China's phosphorous resources. By considering the Chinese realities, we propose the following policy recommendations.

Firstly, to improve the management and utilization of P resources, the Chinese government should formulate more detailed policies, such as optimizing local P mine exploitation, establishing a national list for P products, and stricter regulations for the disposal of P mining waste. Moreover, the market mechanism of phosphogypsum products should be improved to increase the willingness of enterprises to process and produce them. This can be achieved by establishing a standardized list of phosphogypsum products, strengthening product publicity, and improving market recognition. Ultimately, these measures can reduce P resource waste, improve the environment, and increase the overall value of P resources.

Secondly, advanced agricultural management technology is essential for optimizing the efficiency of P resources and enhancing the quality of agricultural planting and livestock husbandry environments. Governments should strengthen cooperation with agricultural planning and technology-related institutions to identify regional advantages and disadvantages of agricultural needs and increase exchanges with agricultural breeders to understand their problems and propose optimal solutions. Additionally, efficient land utilization and larger-scale planting and breeding are essential for improving P efficiency. The circular economy [58] is a viable approach to enhance resource efficiency. The combination of planting and breeding could promote circular agriculture. Aquacultural methods can be also improved by diversifying aquaculture species and feeds, increasing the planting of effective plants in fishponds, and improving soil fertility.

Thirdly, economic measures should be taken to optimize the utilization of P resources. To this end, it is essential to enhance the recognition of organic fertilizers. On the one hand, farmers should be guided to focus more on the long-term benefits of organic fertilizers rather than the short-term gains of chemical fertilizers. On the other hand, it is necessary to formulate effective administrative policies to strengthen the utilization of organic fertilizers. Furthermore, the Chinese government should provide more financial subsidies to organic fertilizer producers in different regions to ease their financial burden and enhance their enthusiasm for improving the quality of their products. By taking these measures, it is possible to improve the utilization of P resources and achieve the goal of optimizing the efficiency of P resources utilization.

4. Conclusions

An increasing population will lead to a surging food demand. At the same time, the excessive waste of P has led to environmental problems. A comprehensive management system for the sustainable development of P resources is essential to address these challenges. This study utilizes the dynamic MFA method and a P resources efficiency index system to analyze the material flows of P resources and the overall utilization of P in China.

The results show that China's phosphate mining has reached its historical highest point and moved towards the green and healthy use of P resources. Since 1990, the P resource efficiency index system has revealed an overall increment in PUE in agricultural planting and product processing modules, PURP in agricultural planting and livestock and poultry breeding modules, PRR of straw, and PRR of human activities as a whole. Nevertheless, the PUE in aquaculture and livestock breeding modules have either decreased or remained relatively stable, suggesting that there is still room for further optimization in these areas. At the same time, the rational application of phosphorus fertilizers needs to fully consider the impact of past phosphorus legacy on the soil, which can effectively improve the effectiveness of phosphorus fertilizers, thereby reducing environmental impact [39].

Based on the results of this study, several recommendations are proposed. First, the Chinese government should formulate more detailed policies, such as optimizing local P mine exploitation policies, establishing a national P product list, and adopting stricter requirements for P mine waste disposal, to optimize the management and utilization of P resources. Second, advanced agricultural management technology is needed to optimize P resource efficiency and enhance agricultural planting and livestock husbandry environments. Strategies such as the circular economy and larger-scale planting and breeding should be adopted to improve P efficiency. Third, economic measures such as enhancing the recognition of organic fertilizers and providing subsidies to organic fertilizer producers should be taken to optimize the utilization of P resources.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture13122262/s1. Figure S1: Chinese phosphorus cycle model framework. Figure S2: China agricultural straw mulching and inventory, 1949–2019. Figure S3: The proportion of countries importing and exporting Chinese phosphate chemical products. (a) Imported phosphorus chemical products in 1995; (b) Exported phosphorus chemical products in 1995; (c) Imported phosphorus chemical products in 1995; (d) Exported phosphorus chemical products in 2010; (e) Imported phosphorus chemical products in 1995; (f) Exported phosphorus chemical products in 2019. Figure S4: Uncertainty analysis results. Table S1: Activity Data. Table S2: Parameter data. Table S3: PUE of agriculture. Table S4. Precycling rate.

Author Contributions: Y.W.: Conceptualization, Methodology, Formal analysis, Writing—Original draft preparation, Writing—Reviewing and Editing J.L.: Conceptualization, Formal analysis, Supervision, Writing—Reviewing and Editing Y.G.: Formal analysis, Supervision, Writing—Reviewing and Editing D.W.: Writing—Reviewing and Editing. All authors have read and agreed to the published version of the manuscript.

Funding: This study is financially supported by the National Key Research and Development Program of China (2019YFC1908501), the National Natural Science Foundation of China (72004134, 72088101, 71810107001), and Shanghai Pujiang Program (2020PJC075).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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