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Effect of Rational Fertilizer for Eggplants on Nitrogen and Phosphorus Pollutants in Agricultural Water Bodies

Peiyuan Luo [1], Changchun Xin [1], Yuanhao Zhu [2], Yang Liu [3], Junhong Ling [1,4], Tianzhi Wang [1,*], Jun Huang [1,*] and Soon-Thiam Khu [1,2,5]

[1] School of Environmental Science & Engineering, Tianjin University, Tianjin 300350, China
[2] Zhejiang Tongji Vocational College of Science and Technology, Hangzhou 310000, China
[3] School of Civil Engineering, Tianjin University, Tianjin 300072, China
[4] Research Institute for Environmental Innovation, Tianjin 300457, China
[5] Engineering Research Center of City Intelligence and Digital Governance, Ministry of Education of the People's Republic of China, Beijing 100083, China
* Correspondence: wangtianzhi@tju.edu.cn (T.W.); huangjun@tju.edu.cn (J.H.)

Abstract: Excessive fertilizer application in the cropping industry leads to excessive nitrogen and phosphorus in surrounding water bodies, which causes farmers to increase economic cost and damage the environment. To address the problem, we built a crop-soil runoff soil column test system, setting eight fertilizer application levels for eggplants. Then, crop yield, soil fertility and pollutant concentrations in the receiving water bodies were measured. The process of fertilizer application on the water quality of surrounding receiving water bodies and the rationality of fertilizer application were analyzed. The results showed that crop yield, soil fertility, and pollutant concentrations in the receiving water increased with the increase in fertilizer application. The crop yield stabilized when the fertilizer application amount was higher than 0.12 kg/m^2; the concentrations of total nitrogen (TN) and total phosphorus (TP) in the water increased significantly with the increase in fertilizer application, where particulate nitrogen (PN) and organic phosphorus (OP) were the key pollutants. In addition, crop growth had an interception effect on pollutant migration. The concentration of pollutants in the water was significantly lower in the late crop growth period (after flowering) than in the early. The crop had the best interception effect on pollutants when the fertilizer application was 0.12 kg/m^2. The concentrations of TN and TP in the water were 29.7% and 22.3% after the flowering period, being lower than those before the flowering period. Therefore, a reasonable value of 0.12 kg/m^2 is recommended for fertilizer application in this article. It can provide a reference for the fertilization system of eggplant planting in North China and theoretical support for the realization of clean production in small rural watershed planting.

Keywords: agricultural surface source pollution; nitrogen and phosphorus pollutant transport; agricultural receiving waters; excessive fertilizer application; clean production

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Citation: Luo, P.; Xin, C.; Zhu, Y.; Liu, Y.; Ling, J.; Wang, T.; Huang, J.; Khu, S.-T. Effect of Rational Fertilizer for Eggplants on Nitrogen and Phosphorus Pollutants in Agricultural Water Bodies. *Processes* **2023**, *11*, 579. https://doi.org/10.3390/pr11020579

Academic Editor: José A. Peres

Received: 4 January 2023
Revised: 20 January 2023
Accepted: 31 January 2023
Published: 14 February 2023

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1. Introduction

As a largely agricultural country, China is accelerating the shift in agriculture from an increased production-oriented system to a quality-oriented one now, realizing the transformation from a large agricultural country to a strong agricultural country. Therefore, the development of green and clean agriculture is of great significance to the construction of a strong agricultural country. However, with the overall progress of rural undertakings, there is the phenomenon of modern agriculture of exchanging environment for development, and the problem of surface source pollution in rural agriculture keeps emerging. The excess nitrogen and phosphorus in surrounding water bodies caused by excessive fertilizer application in the planting industry is a typical problem, with farmers both increasing economic costs and damaging the environment [1,2]. There is no study addressing the problems of high fertilizer input intensity in China's cultivated farmland area, nutrient loss due to higher than optimal fertilizer application, and serious pollution of the watershed water environment [3–5].

In response to these problems, many researchers have combined water conservation, surface source pollution control, and rural waste and sewage treatment [6,7] in the hope of achieving clean and non-eutrophic water bodies and a virtuous ecosystem cycle in small rural watersheds. However, the scale of small watersheds is equivalent to downscaling large watersheds, with the local amplification of conflicts and problems, prominent anisotropy, and increased heterogeneity [8]. For example, the peak point of pollutant content in runoff from small watersheds occurs closer to the peak point of rainfall and has a shorter response time to rainfall. Suspended matter, total nitrogen and total phosphorus showed higher linear correlation in runoff from small watersheds [9]. It causes the technical system of water pollution management in large watersheds to be not adaptable and poorly operable in small watersheds; water quality is more fragile in small watersheds; ecologically clean management measures in small watershed lack a system; water pollution is still serious.

It is the agricultural surface source pollution that is the main cause of the eutrophication of water bodies in small watersheds, contributing to more than 85% of water pollution in the watersheds [10]. As of 2015, the total fertilizer used in China was 5.98×10^{10} kg, accounting for 33% of the world's total fertilizer use, and the amount applied per unit area far exceeded the world average, where the utilization rate of nitrogen fertilizer was about 30–35%, while the utilization rate of phosphorus fertilizer was only 10–20% [11,12]. It means that the excessive use of chemical fertilizers will cause a large number of nutrients such as nitrogen and phosphorus to flow into water bodies, causing eutrophication. When pollutants enter rivers and lakes, even exceeding the self-purification capacity of water bodies, they will deteriorate the water quality and destroy the biological community groups of water bodies, and studies have shown that about 60% of the nitrogen and phosphorus content in surface polluted water bodies comes from chemical fertilizers [13]. For crops, fertilizer application over crop requirements and low fertilizer recovery rates in vegetable crops [14,15] may negatively affect crop yield and fruit size [16] and also lead to health risks (e.g., nitrate accumulation in leafy vegetables, micronutrient deficiencies in crops [17,18]). In conclusion, the problem of rational fertilizer application and control of agricultural surface pollution needs to be urgently addressed.

In recent years, researchers at home and abroad have agreed that four aspects are mainly included with the rational application of fertilizer: the amount of fertilizer applied, the period of fertilizer application, the method of fertilizer application, and the type of fertilizer (the "4R" technique, i.e., right amount, right time, right place, and right type). These four aspects are not isolated but are interrelated and affect each other. For example, the amount of fertilizer applied is determined first and foremost by the target yield, but also by the application method, period, and fertilizer variety [19]. If the latter three are unreasonable, it will contribute to the loss of a large number of nutrients during and after fertilization, which is not fully absorbed and utilized by the crop. To obtain a higher target yield, the farmer has to increase the amount of fertilizer applied to ensure that the crop absorbs enough nutrients. If the latter three tend to be reasonable, then the fertilizer applied can be fully absorbed and used by the crop, and there is no need to add additional fertilizer to "meet the losses". However, the current "4R" fertilization technology does not take into account the impact of fertilizer loss on the surrounding environment and does not form a reasonable value of fertilizer application based on the environmental damage effect of the surrounding water bodies, resulting in the loss of a large number of nutrients during and after fertilization, and the nutrients are not fully absorbed and utilized by the crop. In addition, relevant studies have shown that reducing the amount of fertilizer does not reduce vegetable yield [20,21], which shows that the determination of the reasonable value of fertilizer application has a great positive effect on increasing yield, protecting the environment and reducing costs, especially in areas with large planting areas; the determination of the reasonable value of fertilizer application will largely reduce farmers' fertilizer costs. For example, it has a year-round cash crop cultivation area of 1.19×10^8 m^2

with an annual output value of about USD 2.8 million in Tanchang County, Gansu Province, China. The fertilizer reduction space is huge.

Dimzon et al. [22] determined the water chemistry characteristics of water bodies through information on basic chemical indicators of water bodies (pH, redox potential, electric conductivity (EC), chemical oxygen demand (COD), and other parameters) and the content of substances in the water bodies. They studied regional water chemistry processes through correlations among the indicators. The method is well established and widely used for the study of urban water pollution processes, but the method has obvious limitations for plantation water pollution. Pollution from excessive fertilizer application in the plantation industry is characterized by strong dispersion, stochastic occurrence, and complex pollutant components [23], and current studies have focused on pollutant discharge [24,25], transport [26,27], and transformation processes [28]. Currently, the area of farmland at risk of agricultural surface source pollution in China exceeds 20 billion m^2. The contribution of nitrogen and phosphorus loss in the form of farm runoff to the nitrogen and phosphorus content of river water bodies exceeds 50%, respectively. Gan et al. [29] evaluated the situation of plantation surface source pollution in five counties around Chaohu Lake in Hefei City by monitoring the concentration of nitrogen and phosphorus loss from farmland. The average mass concentrations of TN and TP loss from cultivation in the region in the past three years were 3.48 mg/L and 0.602 mg/L, respectively, which were higher than the water quality standard of surface water category V. The export and pooling of nitrogen and phosphorus in rural sub-watersheds is closely related to the rainfall runoff production process, in which precipitation fully interacts with the soil and the nitrogen and phosphorus fertilizers applied by cultivation interact with rainwater, infiltrated water, and produced water components to influence the export and pooling of nitrogen and phosphorus pollutants to nearby water bodies. Yang et al. [30] monitored the nitrate–nitrogen concentration in rainfall runoff after fertilization and found that peak nitrate–nitrogen concentrations during runoff lagged behind peak confluent flow in surrounding water bodies, and nitrate–nitrogen concentrations in river water appeared to increase after the end of precipitation when runoff from surrounding water bodies gradually dropped back. Buchanan et al. [31] developed a phosphorus index model based on runoff travel time to improve the phosphorus index characterization of the effect of drainage on the potential risk of phosphorus loss. However, these studies could only qualitatively assess the key source areas of nitrogen and phosphorus loss from farmland at the watershed scale, and it was unclear to identify the key impact factors, which resulted in vague conclusions that could only provide the pollution sources that contributed more and could not provide the magnitude of the contribution of specific pollution sources to the water bodies, and could not quantify the pollution of water bodies in small watersheds due to excessive fertilizer application, which lacked practical guidance.

Based on the simulation results of different scenarios of the improved SWAT model, Wang et al. calculated and analyzed nitrate nitrogen and total phosphorus loads under each management scenario and their effects on crop yield, providing a theoretical basis for reducing non-point source pollution in the watershed and improving crop yield. However, this study is only suitable for a large watershed [32]. Li et al. analyzed the amount of fertilizer used in Wuhu City in 2017, calculated the amount of nitrogen and phosphorus lost in planting fields, and proposed problems such as unreasonable traditional fertilization method and fertilization structure, single fertilizer application type and large application amount, low penetration rate of efficient fertilization technology, and proposed and analyzed suitable fertilization technology, but did not propose a solution to the problem of fertilizer amount [33]. The researchers looked at the main factors contributing to the agricultural non-point source pollution and found that the pollution caused by fertilization was greater [34,35]. However, there is no recommendation on the appropriate level of fertilization. Wang et al. determined the temporal and spatial distribution of nitrate and ammonia nitrogen in the watershed by combining water sampling and numerical simulation and predicted the impact of agricultural management measures on reducing river nitrogen pollution [36], but the types of pollutants concerned were limited. Hou et al. established an improved output coefficient model based on rainfall and topography and studied the characteristics of pollution sources and non-point sources of TN and TP in Huangqianku Basin, which is an important drinking water source of the main tributaries of the lower Yellow River [37], and paid less attention to pollutant types [37]. In order to study the change of the content of each form of pollutants in water under different fertilization conditions in a small watershed, the migration pattern of nitrogen and phosphorus pollutants under the fertilization conditions of planting should be clarified, the mechanism of fertilization status on nitrogen and phosphorus pollutants in the receiving water bodies should be obtained, the key pollutants among the various forms of nitrogen and phosphorus pollutants should be found, reasonable values of fertilization in planting by considering nitrogen and phosphorus key pollutants, crop yield and soil fertility should be proposed. This article takes a small watershed as the research unit to carry out the study of the planting industry pollution prevention and control and selects eggplant in a typical small watershed within the Haihe River Basin in North China as the research object. We measured COD, eight nitrogen pollutants (total nitrogen (TN), particulate nitrogen (PN), dissolved total nitrogen (DTN), nitrate nitrogen (NO_3^--N), nitrite nitrogen (NO_2^--N), total Kjeldahl nitrogen (TKN), organic nitrogen (ON), ammonium nitrogen (NH_4^+-N)) and four phosphorus pollutants (total phosphorus (TP), phosphate (PO_4^{3-}), particulate phosphorus (PP), organic phosphorus (OP)) in agricultural runoff by building a crop-soil runoff water system and simulating the actual production and flow production process of the planting industry. The innovation of this article is that the key influencing factors are obtained from seven nitrogen pollutants and three phosphorus pollutants except TN and TP, and the contribution of specific pollution sources to the water body is given. In addition, the pollution caused by excessive fertilization to the water body in a small watershed is quantified. It is concluded that the crop can intercept the pollutants and the optimal fertilizer amount for eggplant planting is 0.12 kg/m^2. It can provide a reference for the fertilization system of eggplant cultivation in North China and provide theoretical support for realizing clean production in small rural watersheds for planting.

2. Materials and Methods

2.1. Crop-Soil Runoff Water Test System

The experiment was conducted in the hydraulic test hall of Tianjin University. The actual production and flow production process of the plantation was simulated by building a crop-soil runoff water system, as shown in Figure 1. The experimental setup used a large Plexiglas soil column to simulate the soil structure of agricultural planting. The soil was taken from the farmland soil of Xi Mengzhuang village section of the rural small watershed, Ji Canal watershed, within the Haihe watershed in North China, and the size of the Plexiglas was 1 m × 1 m × 0.5 m (to ensure the crop grows normally), and the area of the planting unit was 1 m × 1 m; the test crop was selected as eggplant with high water and fertilizer demand and high replanting index.

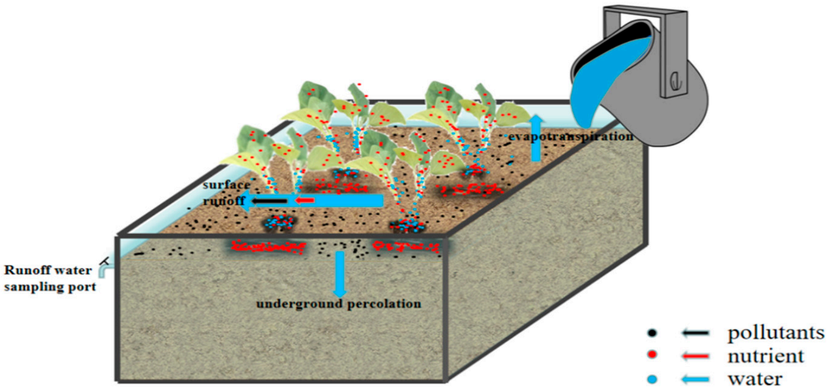

Figure 1. Schematic diagram of experimental equipment for crop-soil runoff water system.

Six fertilization patterns were set in this experiment, and the applied nitrogen fertilizer was calcium ammonium nitrate ($5Ca(NO_3)_2$-NH_4NO_3-$10H_2O$); phosphorus fertilizer was calcium dihydrogen phosphate ($Ca(H_2PO_4)_2$); and potassium fertilizer was potassium chloride (KCl). The fertilization amounts of the six fertilization patterns were shown in Table 1.

Table 1. Fertilization scheme for six plots.

Plot	$5Ca(NO_3)_2 \cdot NH_4NO_3 \cdot 10H_2O$ (kg/m^2)	$Ca(H_2PO_4)_2$ (kg/m^2)	KCl (kg/m^2)	Fertilizer Amount (kg/m^2)
1	0.012	0.009	0.009	0.03
2	0.024	0.018	0.018	0.06
3	0.036	0.027	0.027	0.09
4	0.048	0.036	0.036	0.12
5	0.060	0.045	0.045	0.15
6	0.072	0.054	0.054	0.18
CK	0	0	0	0

The system was irrigated and fertilized six times during the whole reproductive period, and irrigation was carried out 24 h after fertilization, and the amount of irrigation was set as shown in Table 2.

Table 2. Irrigation amount of eggplant at different growth stages (unit: mm).

Date	7.09	7.19	7.29	8.08	8.18	8.28
Growth Period	Planting	Slow seedling	Hardening of seedling	Flowering	Mature 1	Mature 2
Irrigation Amount	5	10	20	60	40	40
Reference	F-7.09	F-7.19	F-7.29	F-8.08	F-8.18	F-8.28

The eggplant was planted with sufficient bottom watering to keep the water in the permeable layer and to keep the soil moist for a long time with a slightly dry surface to prevent high humidity caused by frequent watering, which promoted seedling diseases. As the soil had little water-holding capacity, it was watered properly afterward so as not to allow seedlings to lose water. The seedlings were watered once when they were growing normally to ensure the expansion of the leaves and photosynthesis, thus producing some nutrients for their growth. When it starts to bear fruit, it was watered more frequently to ensure that the eggplants are large and have good color. The first fertilization was on 8 July 2022, planting was on 9 July and harvesting was on 1 September 2022. The specific fertilization dates are 8 July, 18 July, 28 July, 7 August, 17 August, and 27 August. Compound fertilizer was applied before planting and 2/3 of it was applied in general. Then it was plowed deeply and the other 1/3 of the fertilizer was applied and mixed with the soil. Planting is performed on a sunny day, with sufficient water in the furrow and the seedlings were planted after the water has seeped. The plants are spaced 30–35 cm apart and then mulched to a thickness level with the soil pile. Shallow tillage is carried out 3 days after planting to increase the ground temperature and promote the slowing down of seedlings. After the seedlings have slowed down, there was another mid-tillage and mulching, with the mid-tillage making a high monopoly of 12 to 15 cm, so that the monopoly surface was over the heap surface. Nitrogen and potassium fertilizer is applied in combination with watering time. When the eggplant sits in the fruit, then nitrogen fertilizer is applied. The specific experimental process is shown in Figure 2.

2.2. Test Content

2.2.1. Crop Yield

The harvesting period of eggplant in this experiment was from 10 September to 10 October 2022, and it was harvested a total of 4 times. Eggplant harvesting was measured by weighing the single fruit weight of eggplant with an electronic balance (accuracy 0.01 g).

Total output is the sum of four harvests per plot. Then, the number of single plant results was counted, and the average weight of the eggplant was calculated.

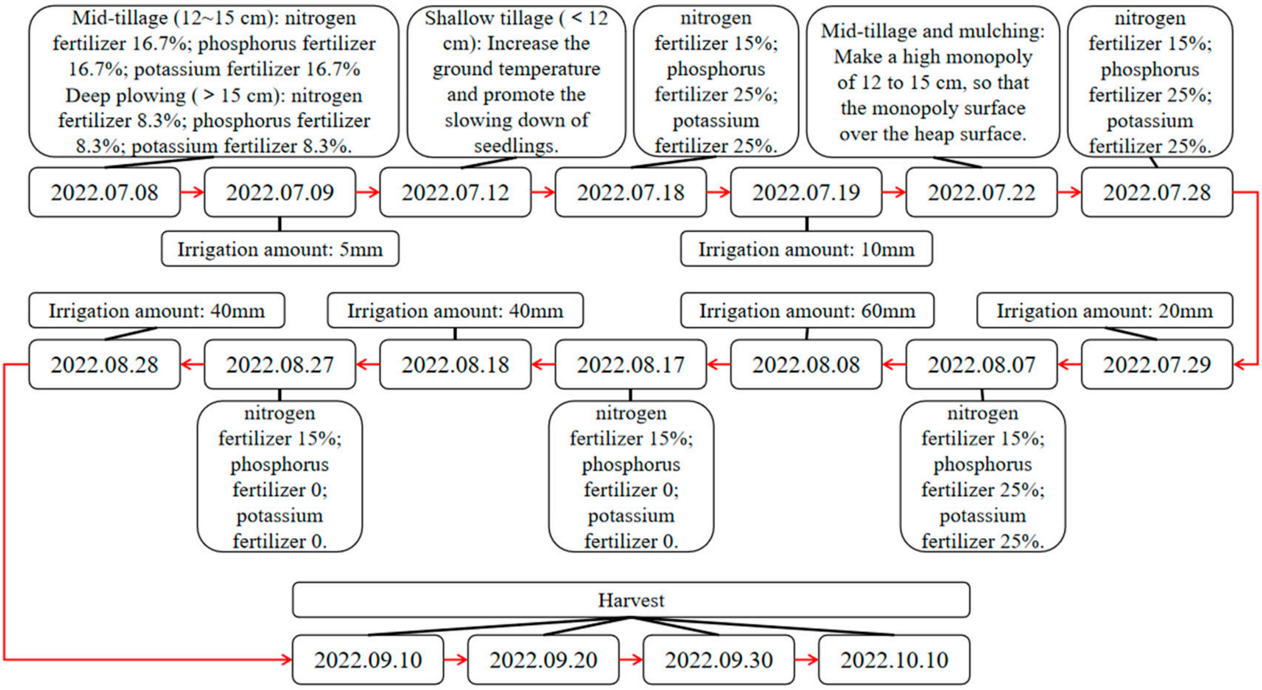

Figure 2. Specific experimental process.

2.2.2. Soil Fertility

Each plot was set up with 3 sampling points according to the principle of triangular uniform sampling, and each sampling point collected 3 surface soil samples to form a mixed soil sample. The soil samples were pretreated by air-drying, grinding, and sieving (<1 mm), and then tested for 5 indicators of soil nutrients, including available nitrogen, available phosphorus, available potassium, pH, and EC, using a soil tester (DK-TF1, Weifang, Shandong, China).

2.2.3. Contaminants in Water

After irrigation each time, runoff water samples were collected at the runoff water sampling port, and the collected samples were transferred into clean and dry sampling bottles, sealed with labels and numbers, and then transported back to the laboratory at a low temperature for the determination of different forms of nitrogen and phosphorus pollutants within 72 h. The indicators included COD, TN, TP, seven nitrogen pollutants (PN, DTN, NO_3^--N, NO_2^--N, TKN, ON and NH_4^+-N), and three kinds of phosphorus pollutants (PO_4^{3}-, PP and OP). The determination methods of pollutants are shown in Table 3.

2.2.4. Statistical Analysis

In this article, one plot was set for one fertilizer application; the content of available nitrogen, phosphorus, potassium, and the content of pollutants in water were taken three times and then the average value was obtained using Matlab-2019. The total production of eggplant was the sum of the four times harvests, and the single yield of eggplant was the ratio of total production of eggplant and the number of eggplants in each of the four times harvests. These data were plotted by Matlab-2019. In addition, the correlation diagram between pollutants and fertilizer amounts were manufactured by Origin-2022.

Table 3. The determination methods of pollutants.

Indicator	Method
TN	KH_2PO_4 oxidation—ultraviolet spectrophotometry
PN	The difference between TN and DTN
DTN	1. Filter with 0.4 μm filter hole 2. KH_2PO_4 oxidation—ultraviolet spectrophotometry
NO_3^--N	Phenol disulfonic acid photometry
NO_2^--N	N-1-Naphthylethylenediamine Dihydrochloride spectrophotometry
TKN	The difference between NO_3^--N and NO_2^--N
ON	The difference between TKN and NH_4^+-N
NH_4^+-N	Nessler's reagent spectrophotometry
TP	1. KH_2PO_4 digestion 2. Molybdenum-antimony resistance spectrophotometry
PO_4^{3-}	1. Filter with 0.4 μm filter hole 2. Mo-Sb Anti-spectrophotometer
PP	EDTA method
OP	1. Extracted by chloroform several times 2. Gas chromatography
COD	Potassium dichromate method

3. Results

3.1. Effect of Fertilizer Application on Soil Fertility in Plantation

The change in soil fertility with the increase in fertilizer application in different planting periods is shown in Figure 3.

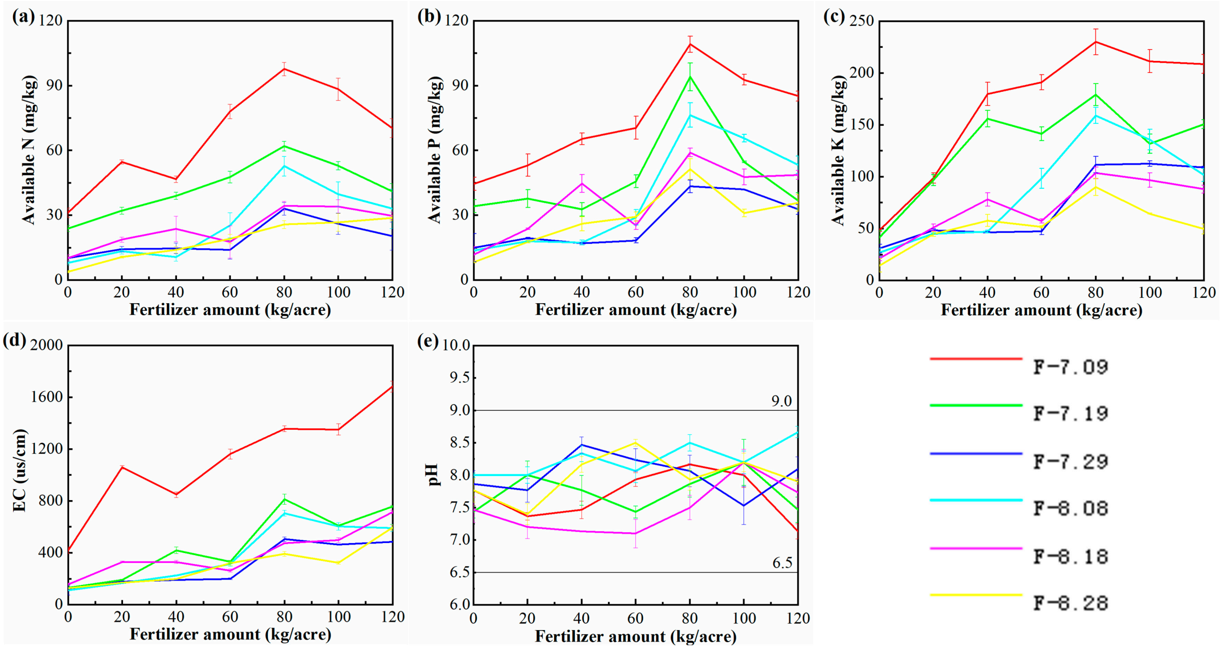

Figure 3. Relationship between soil fertility and fertilizer amount.

It can be seen that the highest content of available P in soil fertility was 96.5 mg/kg, which was 194.2% and 128.0% higher than the content of available N and available P, respectively. With the increase in fertilizer application, the content of available N, available P, and available K in the soil first increased and then decreased, and the highest content of available N, P, and K was found at 0.12 kg/m^2 with the average value of 50.9 mg/kg, 72.2 mg/kg, and 145.6 mg/kg, which were 36.9%, 48.3%, and 23.4% higher than that at 0.18 kg/m^2, respectively. Compared with the CK group (fertilizer application was 0), the available N, P, and K content increased 249.4%, 240.3%, and 378.9% at 0.12 kg/m^2, respectively. Soil EC showed a gradual increase with increasing fertilizer application, and the highest EC content was 804.6 µs/cm at 0.18 kg/m^2, which was 356.3% higher than that of the CK group. The variation in soil pH was independent of the fertilizer application amount and was in the range of 6.5 to 9.

In addition, when the fertilizer application was 0.12 kg/m^2, the available N, P, and K contents and EC generally showed a decreasing trend with the growth of the crop, but the flowering stage was more special, and the soil fertility at the flowering stage was higher than that at the hardening of the seedling and mature stages. The available N, P, and K contents and EC values at the flowering stage were 59.6%, 76.2%, 42.4%, and 39.6% higher than those at the hardening of the seedling, and 75.6%, 38.4%, 64.2%, and 62.9% higher than those at the mature stage, respectively.

3.2. Effect of Fertilizer Application on Crop Yield in Plantation

The relationship between eggplant yield and fertilizer application is shown in Figure 4.

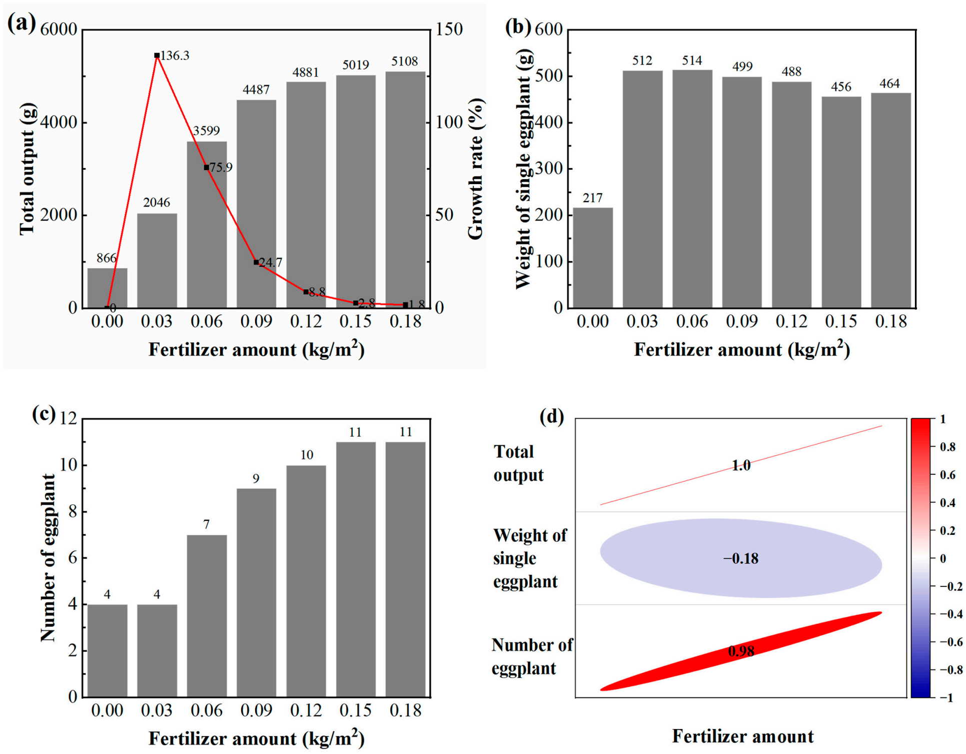

Figure 4. Relationship between fertilizer amount and total output, the weight of single eggplant, number of eggplants, and the correlation between them and fertilizer amount.

From Figure 4a, it can be seen that the total eggplant yield showed an increasing trend with the increase in fertilizer application, and the increase in eggplant yield showed a decreasing trend with the increase in fertilizer application. From Figure 4b, for individual eggplant weight, the individual eggplant weight of all fertilizer application groups was much higher than that of the CK group. When the fertilizer application amount was 0.03 kg/m^2~0.12 kg/m^2, the difference between individual eggplant weight was small and distributed in 488.0 g/unit~514.0 g/unit; when the fertilizer application amount was 0.12 kg/m^2~0.18 kg/m^2, the individual eggplant weight was significantly lower and the average weight was distributed from 464.0 g/unit to 488.0 g/unit; when the fertilizer application was 0.12 kg/m^2, the weight of individual eggplant was 488 g/unit, which was

5.1% higher than that when the fertilizer application was 0.18 kg/m^2. In addition, it can be seen from Figure 4c that the number of eggplants increased all the time with the increase in fertilizer application, with a minimum of four and a maximum of eleven. When the fertilizer application was 0.12 kg/m^2, the number of eggplants was 10, which was close to the optimal level. From Figure 4d, it can be seen that the correlation between the total output and the fertilizer amount was the highest (1) followed by the number of eggplants (0.98). The weight of single eggplant was negatively correlated with fertilizer amount and the value was small (−0.18).

3.3. The Effect of Fertilizer Application on Nitrogen and Phosphorus Pollutants in the Surrounding Water Bodies

The process of the influence of fertilizer application amount on pollutants in the receiving water bodies is shown in Figure 5.

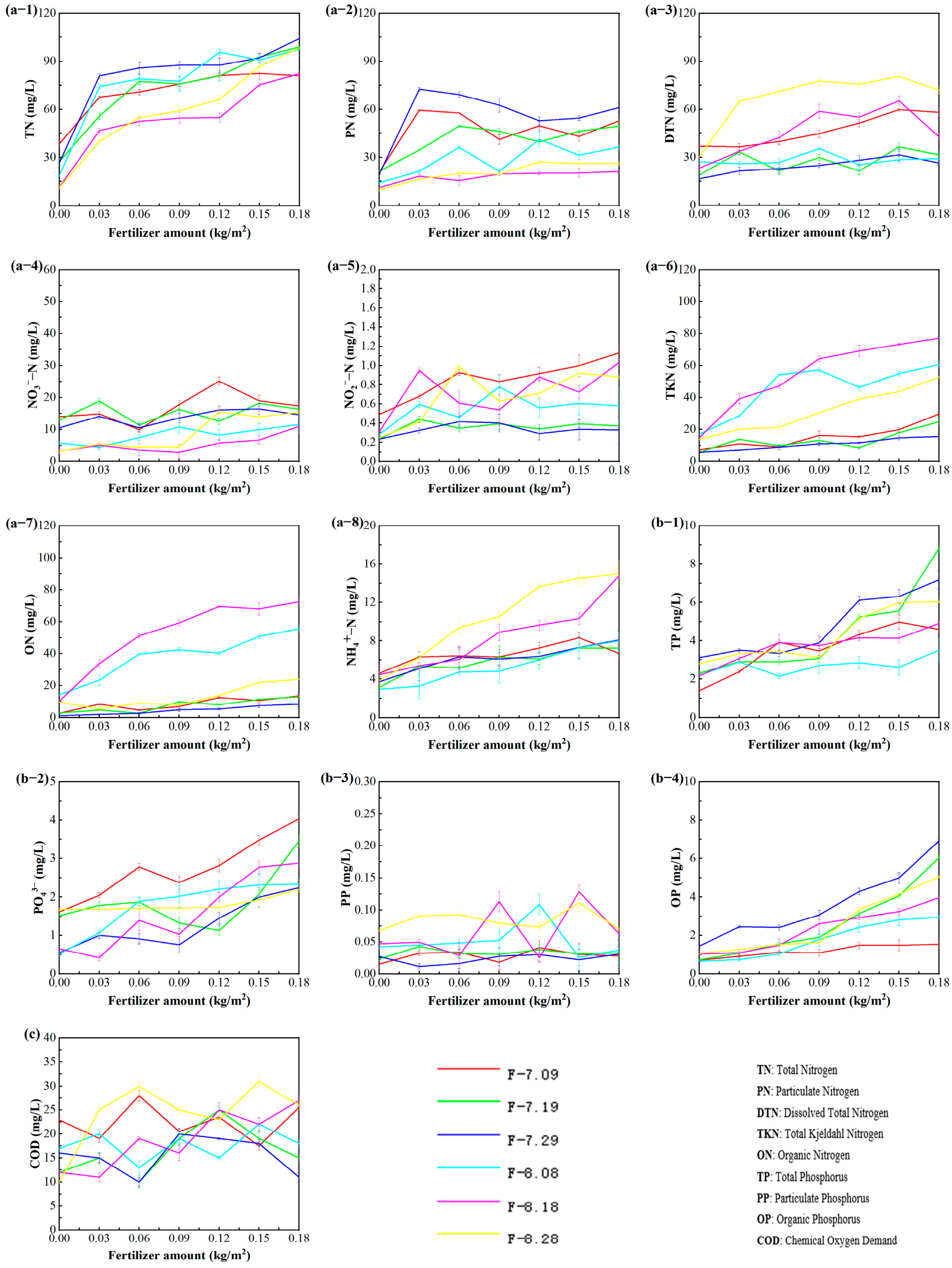

Figure 5. Relationship between fertilizer amount and pollutant concentration in runoff.

With the increase in fertilizer application amount, the TN and TP concentrations in the receiving water body showed an increasing trend, and at 0.18 kg/m^2, the TN and TP concentrations were the largest at 93.7 mg/L and 5.85 mg/L, which were 318.0% and 151.0% larger than the CK group, respectively, and the COD concentration did not change significantly at 15.0 mg/L~20.4 mg/L. For nitrogen pollutants, the order of pollutant concentrations in the water column was DN > PN > TKN > ON > NO_3^--N > NH_4^+-N > NO_2^--N except for TN, where the concentration of NO_2^--N was extremely low, only 1/100 of TN. Among the top four nitrogen pollutants with larger concentrations, TKN and ON were similar to TN in terms of concentration changes, and gradually increased with the increase in fertilizer application, and at 0.18 kg/m^2, the concentrations of TKN and DN were the largest, 43.4 mg/L and 43.3 mg/L, respectively, which were 303.2% and 70.0% larger than the CK group, respectively. Among these pollutants, OP and PO_4^{3-} were similar to TP and showed an increasing trend with the increase in fertilizer application, and the concentrations of OP and PO_4^{3-} were the largest at 0.18 kg/m^2, 4.6 mg/L and 2.9 mg/L, respectively. which were 390.2% and 128.2% greater than the CK group, respectively.

In addition, with the growth of the crop, the concentrations of PN and DN in the water fluctuated from planting to flowering, with PN decreasing and then increasing from flowering to maturity, and DN increasing from flowering to maturity; ON and TKN decreased from planting to hardening of the seedling, then increased until maturity one, and decreased again at maturity two. TN increased from planting to flowering, decreased at maturity one, and increased again at maturity two. TN increased from planting to flowering, decreased at maturity one, and increased again at maturity two. The TN and PN concentrations in water at maturity were 60.6 mg/L and 23.6 mg/L, respectively, which were 20.5% and 18.0% lower than those at flowering.

The trends of TP, OP, and PO_4^{3-} were fluctuating during the crop growth period, with TP and OP increasing significantly from the planting stage to the hardening of the seedling stage, decreasing at the flowering stage, and increasing again at the mature stage, and PO_4^{3-} conversely. The concentrations of TP and OP in the water at the flowering stage were 2.9 mg/L and 2.4 mg/L, respectively, which were 53.3% and 47.6% lower than those in the hardening of the seedling stage, indicating that the concentration of phosphorus pollutants in the receiving water changed more than that of nitrogen pollutants during the crop growth.

4. Discussion

The improvement in crop yield is first of all the result of crop variety renewal; after most varieties reach their required maximum yield fertilizer application, then increasing the fertilizer application will no longer have a yield increasing effect, and only new varieties with stronger fertilizer tolerance can ensure that the fertilizer application beyond the originally promoted varieties still has a yield increasing effect [38]. In addition, this experiment found that the increase in eggplant yield with increasing fertilizer application showed a decreasing trend with increasing fertilizer application. When the fertilizer application was higher than 0.12 kg/m^2, the weight of individual eggplants decreased significantly, which is consistent with the findings of Zhang et al. [39] and Xiao et al. [40]. They found that they were more sensitive to fertilizer tolerance, and excessive fertilizer application did not improve their yield and quality and even granularity. In this paper, we found that with the increase in fertilizer application, the content of available N, available P, and available K increased to the maximum when the fertilizer application was 0.12 kg/m^2 by analyzing the correlation between the eggplant yield and soil fertility. When the fertilizer application was higher than 0.12 kg/m^2, the content of available N and available P in the soil fertility decreased, and the content of nitrogen and phosphorus nutrients that could be absorbed by crops in the soil decreased. N is the main element of protein, nucleic acid, and phospholipid in living cells of crops, and is one of the constituent elements of chlorophyll, which has an important impact on crop photosynthesis. Phosphorus is beneficial to the smooth transition of plants from nutritional growth to reproductive growth, promoting the formation of reproductive organs and early flowering and fruiting; thus, nitrogen and phosphorus are essential for crop growth. Therefore, when the fertilizer application amount is higher than 0.12 kg/m^2, the eggplant yield no longer increases, and even the quality of the individual eggplants decreases.

In addition, the concentration of nitrogen and phosphorus pollutants in the receiving water bodies tended to increase with the increase in fertilizer application, which was due to the low utilization of nitrogen and phosphorus in the fertilizers used on the crops in this study, spreading fertilizers and the low nutrient utilization efficiency of vegetable crops because of their short growth time [41]. A large amount of nitrogen and phosphorus elements entered the receiving water bodies with runoff, causing water decent source pollution. In this paper, the relationships between eight nitrogen pollutants and four phosphorus pollutants were analyzed separately (Figure 6), and it was found that particulate nitrogen (PN) was the key nitrogen pollutant and organic phosphorus (OP) was the key phosphorus pollutant in the water. Nitrogen substances in fertilizers are transformed through decomposition by soil microorganisms to produce organic nitrogen, nitrate nitrogen, ammonium nitrogen, and particulate nitrogen. The inability of crops to utilize PN and the low utilization of DTN make the loss of PN and DTN the main forms of nitrogen loss from farmland [36]. DTN is mainly found in two forms: NH_4^+-N and NO_3^--N, and under aerobic conditions, NH_4^+-N is quickly oxidized to NO_3^--N. One part is absorbed by crops and the other part is adsorbed by soil colloids into the receiving water body with runoff, which makes the concentration of PN and DTN in the water higher, but the correlation between PN and TN is higher, which can be used as a key nitrogen pollutant in the receiving water body under different fertilizer application conditions. Phosphorus fertilizer application to soil is accompanied by a series of complex chemical and biological processes, including the mineralization of organic phosphorus and the biological fixation of inorganic phosphorus, the fixation of effective phosphorus, and the release process of insoluble phosphorus [42]. More phosphorus in the soil is released through the mineralization of organic phosphorus compounds, and then plants take up phosphorus from the soil solution as $H_2PO_4^-$ and HPO_4^{2-} with different efficiencies. The unmineralized organic phosphorus remains partly in the soil and partly excreted as runoff. It makes OP a key phosphorus contaminant in receiving waters.

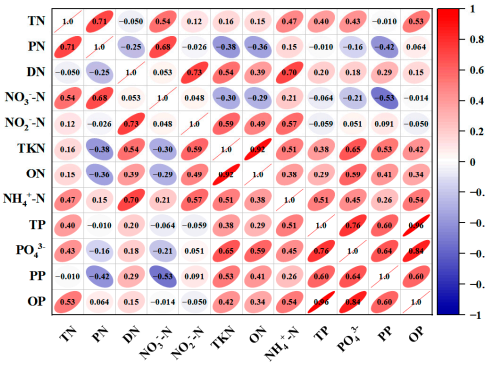

Figure 6. Correlation between different forms of nitrogen and phosphorus pollutants.

In addition, we found that during the flowering stage, the crop has the best interception effect on PN, TP, and OP, which can be reduced by 21.9%, 53.3%, and 47.6%, respectively, while during the maturity one, the interception effect on TN is the best, and the concentration can be reduced by 42.6%, indicating that crop growth will have a certain interception effect on the pollutant migration. The first point is due to the need for nutrients such as nitrogen and phosphorus for crop growth; the nitrogen absorbed by plants is mainly inorganic nitrogen, including ammonium nitrogen and nitrate nitrogen. Although low concentrations of nitrite can also be absorbed by plants, it is inherently absorbed in small amounts and high concentrations are harmful to plants and have no real nutritional value. Total nitrogen, total phosphorus, and organic phosphorus concentrations in water decrease the most during flowering and maturity because of increased root uptake and nutrient utilization capacity in late plant growth; Nendel et al. [43] found that in dry or temperate environments, potentially mineralized nitrogen accounts for a higher proportion of total soil nitrogen, and crops use fewer nutrients from fertilizer, the available N, P, and K originally contained in the soil are preferentially absorbed and used by crops resulting in larger concentrations of TN, TP and OP in runoff during the early stages of crop growth. In addition, soil fertility varies under different soil types. The soil used in the experiment is loam, which has good tillability, has the advantages of sandy soil and heavy loam, and has significantly higher soil fertility than heavy loam, which is more suitable for crop growth and development [44]. Chen et al. found that the comprehensive fertility of different soil types was yellow soil > paddy soil > lime soil > purple soil when exploring the relationship between soil types and soil fertility in a citrus orchard [45], which was also the reason why there were more available N, P and K in crop utilization soil. The number of microorganisms in the soil also affects the soil fertility. Chen et al. took tea trees of different planting years as research objects and found that there was a correlation between the number of microorganisms in rhizosphere soil and some soil fertility indexes [46]. The number of soil bacteria was significantly correlated with the soil organic matter and total phosphorus; the number of fungi was not significantly correlated with the soil nutrients; the number of actinomyces was significantly correlated with soil nutrients; the number of soil microorganisms reflected the level of soil fertility at a certain level [47]. Therefore, there may be more microorganisms in the soil selected in the experiment, and the soil fertility is higher, which provides part of the nutrients for the early growth of crops. In addition, irrigation water may also contain significant amounts of N. For example, a typical seasonal irrigation volume for sweet pepper is approximately 0.3 $m^3 \cdot m^{-2}$ with a nitrate concentration of 50 $mg \cdot L^{-1}$, corresponding to a total N input of 0.0034 $kg \cdot m^{-2}$ [48], and in this study crop growth could directly utilize inorganic nitrogen in water and utilize less nitrogen in the fertilizer, resulting in a larger total nitrogen concentration in the water at the beginning of crop growth and not showing a greater interception effect until maturity one. Second, we reduced irrigation from 60 mm to 40 mm at maturity and reduced irrigation, directly reducing the amount of leachate, which then promotes root growth [49–51], it may also increase plant uptake of water and nutrients [52] and reduce N and P leaching. On the other hand, reduced irrigation harms soil microbial load, microbial diversity, and enzyme activity [53], thereby inhibiting the conversion of N and P, which also helps to reduce their leaching. The second reason why crop growth would have an interception effect on pollutant transport is that crop roots precipitate particulate matter in water, and in this study, the degree of PN interception by the crop was greatest at flowering. Yang et al. [54] showed that plants not only remove some of the N and P from water through uptake but also precipitate the particulate matter by reducing the flow rate due to the well-developed root system of the crop and the substrates.

Finally, this paper discusses reasonable fertilization in the process of eggplant planting by combining the interrelationship between fertilization, the amount of soil, the crop fertility, and the environmental effects on the yield. When the fertilizer application amount was 0.12 kg/m^2, the soil fertility was better, and the available N, P, and K increased by 249.4%, 240.3%, and 378.9% compared with the CK group; the soil EC value can play a guiding role in plant fertilization and can reflect the actual condition of the soil salinity, which affects the transformation, existence state, and effectiveness of the soil nutrients and is the threshold value limiting plant and microbial activity. Relevant studies have shown that the optimal range of soil EC required for eggplant cultivation is 500 μs/cm to 750 μs/cm. In this study, when the fertilizer application rate was 0.12 kg/m^2, the soil EC was 710 μs/cm, which met the requirements for eggplant cultivation. Considering crop yield, when the fertilizer application amount was less than 0.12 kg/m^2, the increase in fertilizer application could promote crop growth, and when the fertilizer application amount was greater than or equal to 0.12 kg/m^2, the total yield remained the same, indicating that the fertilizer application amount was no longer a key factor limiting crop yield, but when the fertilizer application amount was higher than 0.12 kg/m^2, the yield of the individual eggplants would decrease. Considering environmental pollution, with the increase in fertilizer application, the concentration of pollutants also increases, but the main nitrogen and phosphorus pollutants all slow down the growth and tend to balance when the fertilizer application is 0.12 kg/m^2; when the fertilizer application is higher than 0.12 kg/m^2, the concentration of total nitrogen and phosphate increases significantly, which will pollute the water body to a great extent and bring pressure to the surrounding environment. Therefore, after considering the soil fertility, crop yield, and environmental pressure, the reasonable value of fertilizer application for eggplant planting is 0.12 kg/m^2.

The limitation of this study is that the influence of soil microorganism quantity on the soil's available nitrogen, phosphorus, and potassium for eggplant growth was not considered when exploring the influence of fertilizer amount on the soil's available nitrogen, phosphorus, and potassium. Our research group is designing related experiments to study the effect of soil microorganism quantity on the soil's available nitrogen, phosphorus, and potassium content, and further improve the part of the study on the effect of fertilizer application on available nitrogen, phosphorus, and potassium content.

5. Conclusions

This article takes eggplant in a typical small watershed within the Haihe River Basin in North China as the research object; we study the changes in crop growth and the content of various forms of pollutants in the receiving water under different fertilizer application amounts by building a crop-soil runoff water system and obtain the following conclusions.

(1) The key nitrogen and phosphorus pollutants are PN and OP, respectively. The average proportion of PN to TN is 50.9% and the average proportion of OP to TP is 60.6%.
(2) Crop growth will have a certain interception effect on pollutant migration. At the flowering stage, PN, TP, and OP were intercepted best by the crop, which can be reduced by 21.9%, 53.3%, and 47.6%, respectively, while TN was intercepted best at maturity one, and the concentration could be reduced by 42.6%.
(3) Combining the interrelationship between fertilizer application on soil, crop fertility, and environmental effects on yield in the process of eggplant planting, the reasonable value of fertilizer application for eggplant planting in this paper is suggested to be 0.12 kg/m^2. At this time, the soil fertility is the highest, the yield is close to the maximum, and the crop has the best interception effect on pollutants.

Author Contributions: Conceptualization, Established the research line and supervised the current work, T.W.; Performed the experiments and Data curation, C.X.; Writing-Reviewing and Editing, P.L.; Guide data analysis, Y.Z. and Y.L.; Guide drawing, J.L. and J.H.; Visualization, Supervision, S.-T.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Fund Independent Innovation Fund of Tianjin University [2022XSU-0030, 2022XZ-0019]. And The APC was funded by J.H.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: We are grateful for the financial support from the National Natural Science Fund Independent Innovation Fund of Tianjin University (2022XSU-0030, 2022XZ-0019). All individuals included in this section have consented to the acknowledgement.

Conflicts of Interest: The authors declare no conflict of interest.

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