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A Sustainable Way of Fertilizer Recommendation Based on Yield Response and Agronomic Efficiency for Chinese Cabbage

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Abstract: Chemical fertilizer plays an irreplaceable role in raising vegetable output and improving the livelihood of people in China. Chinese cabbage (*Brassica chinensis* L.) is one of the most common vegetables with a wide planting area. However, there are problems such as the excessive and blind application of chemical fertilizers, which bring about the increase of planting cost and the risk of environmental pollution. So, it is urgent to improve fertilization methods and improve fertilizer use efficiency, aiming to promote the sustainable development of agriculture. In this study, multi-year and multi-site experiments were retrieved from the published literature and public scientific research institutions to study a sustainable fertilizer recommendation method for Chinese cabbage based on yield response and agronomic efficiency. The results showed that the average indigenous nutrients supply of nitrogen (N), phosphorus (P), and potassium (K) were 112.98, 35.03, and 213.15 kg/ha, respectively. It is suggested that these nutrients should not be neglected in the process of fertilizer recommendation. The average yield responses to N, P_2O_5, and K_2O were 26.6, 13.9, and 16.6 t/ha, the relative yields were 0.70, 0.84, and 0.84; also, it was concluded that the agronomic efficiencies were 114.3, 108.5, and 89.4 kg/kg on average, respectively. From these datasets, the theoretical basis of recommended fertilization was established. It was found that there was a significant negative correlation between N, P, and K indigenous nutrient supply and the yield response to N, P_2O_5, and K_2O, and a significant negative linear correlation between yield response and the relative yield of N, P_2O_5, and K_2O. There was also a significant one-dimensional quadratic function relationship between yield response and agronomic efficiency in Chinese cabbage. Then, two years of field experiments for Chinese cabbage were conducted to verify the fertilizer recommendation. It was concluded that fertilizer recommendation for Chinese cabbage based on yield response and agronomic efficiency was a sustainable way for farmland utilization, not only economically and suitably satisfying its application on fields of different sizes, but also taking into account the indigenous nutrient supply and the interaction between N, P, and K, having shown the advantages of high efficiency, especially when the conditions such as soil testing and plant diagnosis were not sufficient.

Keywords: fertilizer application; agronomic efficiency; yield response; recovery efficiency; sustainable farmland utilization

1. Introduction

Chemical fertilizer plays an irreplaceable role in raising grain and vegetable output and improving people's livelihoods, which is an indispensable determinant of yield increase, with the contribution to yield increase as high as 50%. However, while ensuring food security and promoting the development of agricultural production, there are problems such as the excessive and blind application of chemical fertilizer, which brings about the increase of planting cost and the risk of environmental pollution. So, it is urgent to improve fertilization methods, improve fertilizer use efficiency, reduce unreasonable input, and ensure the effective supply of major agricultural products, all of which promote the sustainable development of agriculture.

Chemical fertilizer is closely related to the sustainable development of agriculture. In order to realize the sustainable development of agriculture, scientists have focused their research on how to use chemical fertilizer scientifically and reasonably, how to improve the utilization efficiency of fertilizer, and how to reduce the negative effects and adverse effects brought on by chemical fertilizer. In 2015, the Action Plan for Zero Increase in Chemical Fertilizer by 2020 was formulated in China, and it was proposed that a scientific fertilization management and technology system should be preliminarily established by 2020, so that the scientific fertilizer application level could be significantly improved [1]. One of the tasks is to promote precision fertilization. According to the requirements of soil conditions, crop yield potential, and nutrient comprehensive management in different regions, the standard of fertilization limit amount per unit area for crops should be rationally formulated to reduce the behavior of blind fertilization.

Vegetable is one of the indispensable food sources for the residents, which occupy the largest per capita consumption in China, and is also the second largest crop in production following the grain crop, contributing the most to the growth of per capita disposable income of rural residents in the country. In recent years, the vegetable industry has developed rapidly in China, generally meeting the growing demand of urban and rural residents for the quantity, quality, and variety of vegetables. In 2017, the sown area of vegetables in China was 19.98 million hectares, with an output of over 692 million tons, which has shown a steady upward trend in the past 10 years [2]. By 2020, the vegetable area will be stable at about 21.3 million hectares, out of which 4.2 million hectares are facility vegetable [3]. Chinese cabbage (*Brassica chinensis* L.) is one of the most common vegetables with a wide planting area of 2.64 million hectares in 2017, accounting for 13.21% of the vegetable sowing area. There have been excessive and unbalanced fertilization phenomena on cabbage, which leads to the low utilization of fertilizer and no obvious benefit to the increase of farmer income.

A great deal of research has been carried out on the recommended fertilization of crops, and a variety of recommended fertilization methods have been developed, such as soil-testing, fertilizer effect function, site-specific nutrient management, among others [4]. However, there are some deficiencies in the current recommended fertilizer application methods for crops. For example, soil-testing based fertilizer recommendation needs the collection of soil samples and laboratory tests and analysis, which takes a long time and is expensive. Under the conditions of short crop rotation time and small-scale farmers as the main business units in China, its application is limited. The fertilizer effect function method needs experiments to be carried out and validated by different fertilizer application amounts in the early stage, but different soil properties, different fertility, and different climates will have an influence on the recommended fertilizer application amount [5]. Therefore, it is urgent to establish a convenient and suitable recommended fertilization method.

Fertilizer recommendation based on crop yield response and agronomic efficiency do not need soil testing, and it can be made in a few minutes based on specific planting information for specific plots, which is convenient and suitable for smallholders, family farms and other large-scale operations and planting. The specific local production and climate conditions were combined to consider when making fertilizer recommendation. The yield response refers to the yield difference between the treatment of applying nitrogen, phosphorus, and potassium fertilizer and the treatment of nitrogen, phosphorus, or potassium fertilizer omitted. Agronomic efficiency refers to the economic yield that can be increased by applying 1 kg of N, P_2O_5, or K_2O nutrients. Fertilization method based on yield response and agronomic efficiency suggests that the yield achieved by a crop after fertilization is mainly composed of two parts, one of which is the yield produced by the supply of soil indigenous nutrients (which can be characterized by the treatment of deficiency of certain nutrients), and the other part is the yield increased by fertilization [5].

The principle of fertilizer recommendation based on yield response and agronomic efficiency is that the nutrient absorption or yield level of plot without fertilization is used to characterize the soil basic fertility. The greater crop yield response after fertilization on the plot, the lower soil basic fertility, and it will result in a higher amount of fertilizer being recommended. For the nitrogen fertilizer recommendation, it is based mainly on the correlation between crop agronomic efficiency and yield response, and adjusted appropriately based on the specific information of the block; in the case of phosphate and potash fertilizer recommendation, the calculation is based mainly on the amount of nutrient required for crop yield response and the amount of nutrients required to supplement crop aboveground removal. The nutrients brought in by returning the crop straw to the field are also taken into consideration in the recommended dosage.

A database including growth characteristics and agronomic characteristics of different crops was constructed on the basis of multi-point and multi-year experiments in China. Fertilizer recommendation based on yield response and agronomic efficiency is according to the characteristics of soil indigenous nutrient supply, the internal relationship between crop agronomic efficiency and yield response, the best nutrient absorption and utilization characteristic parameters of crops with universal guiding significance, and combined with local production conditions.

The purpose of fertilizer recommendation is to coordinate the balance input of nitrogen (N), phosphorus (P), and potassium (K) and medium and trace elements, also to ensure crop yield, improve fertilizer use efficiency, and reduce nutrient loss to the environment. In addition, this method not only timely satisfies the applicability of recommended fertilizer for fields of different sizes, but also takes into account the indigenous nutrient supply and the interaction between N, P, and K, showing the advantages of high efficiency, easy grasping, and wide application, especially when the conditions such as soil testing and plant diagnosis are not sufficient.

At present, the recommended fertilization method based on yield response and agronomic efficiency has been applied to maize (*Zea mays* L.) in foreign countries [6,7]. Since 2009, the recommended fertilization of maize, wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), soybean (*Glycine max* L.), potato (*Solanum tuberosum* L.), and radish (*Raphanus sativus* L.) based on yield response and agronomic efficiency has been carried out in China [8–16]. The results of multi-year field experiments show that this method can reduce the application of nitrogen and phosphorus scientifically, improve the fertilizer utilization rate, promote the balanced application of potassium fertilizer, and increase farmers' income on the premise of ensuring crop yield. Especially when the soil test conditions are not available or the test results are not timely, this method is a new method of optimum fertilization guidance, which has been warmly welcomed by farmers and scientific and technological personnel.

However, the application of this method in Chinese cabbage is still unknown, and the parameters needed in Chinese cabbage still need to be studied and corrected according to China's unique vegetable yield and nutrient absorption characteristics, soil information, and nutrient management measures. In order to improve the yield and quality of Chinese cabbage under the win–win mode of economic and environmental benefits, it is urgent to study the recommended fertilization parameters suitable for Chinese cabbage and develop independent recommended fertilization methods for scientific guided fertilization in the current intensive production system.

Based on the unreasonable current situation of vegetable fertilization in Chinese cabbage, this study aims to:

i. Analyze the characters of indigenous nutrients supply, relative yields, yield responses, and agronomic efficiencies of N, P, and K for Chinese cabbage;
ii. Make the theoretical basis of recommended fertilization based on yield response and agronomic efficiency;

iii. Carry out field experiments and valid the fertilization method and feasibility based on yield response and agronomic efficiency without soil-testing, which could make fertilizer recommendation for a specific plot possible within a few minutes.

The results can provide theoretical and technical guidance for scientific fertilization of Chinese cabbage, and provide support for reducing fertilizer, increasing efficiency, and realizing the "zero growth" of fertilizer in China.

2. Materials and Methods

2.1. Data Source

The powerful database supporting fertilizer recommendation is the collection of published literature on Chinese cabbage from 2000 to 2018, and published or unpublished datasets from the International Plant Nutrition Institute. The experiments involved included different treatments, i.e., farmers' practice treatment, optimal nutrient management treatment, N, P, or K nutrient omission treatment, different levels of fertilizer application treatment, inorganic and organic fertilizer mixed application treatment, and long-term field experiments. The parameters recorded included the yield production, N, P, and K fertilization rates, N, P, and K nutrient content, and total N, P, and K nutrient uptake in plant, and pH, total nitrogen, organic matter, available nitrogen, phosphorus, and potassium content in the experimental soil.

The data collected were from all Chinese cabbage growing areas in China, including a wide range of soil types and climatic conditions. After screening and sorting out the sample data, a total of 296 experimental sites were collected, and the main collected datasets (number of experiments >10) are listed in Table 1. The other 85 experimental sites were distributed in 17 other provinces (each province with less than 10 sample points) and were not listed in detail. The varieties in the experiments were all commonly used in local production and highly represent the great variation in cabbage production.

Table 1. The climate characters of main collected experimental sites for Chinese cabbage.

Province [1]	No. of the Experiments	Latitude	Longitude	Precipitation (mm)	T_{min} [2]	T_{max} [3]
Hebei	35	38.04	114.51	350–500	−2.5	26.9
Guizhou	25	26.60	106.71	688–1480	4.1	24.3
Tianjin	21	39.09	117.20	550–600	−4.4	27.5
Beijing	20	39.90	116.41	550–650	−4.2	27.5
Shandong	20	36.67	116.99	550–950	−1.5	27.7
Jiangsu	19	32.06	118.80	800–1200	3.1	29.1
Fujian	16	26.10	119.30	765–2084	11.1	29.0
Yunnan	16	25.05	102.71	584–2700	7.9	20.8
Henan	14	34.75	113.62	500–900	0.5	28.9
Chongqing	13	29.57	106.55	1000–1450	8.2	30.8
Hunan	12	28.23	112.94	1200–1750	4.6	28.9

[1] Other provinces with less than 10 sample points were not listed in detail; [2] T_{min}: Minimum monthly mean temperature; [3] T_{max}: Maximum monthly mean temperature.

2.2. Overview of Field Validation

The multiple sites for the experiments were conducted in farmers' fields in Hebei (115°48′ E, 39°15′ N), Shandong (117°04′ E, 36°11′ N) and Beijing (Lichun 116°24′ E, 39°39′; Weizhuang 116°19′ E, 39°38′ N and Zhangziying 116°35′ E, 39°41′ N) in the year 2017 and 2018 to validate the feasibility of fertilizer recommendations based on yield response and agronomic efficiency. These experiments were located on fluvo-aquatic or sandy soil. The Chinese cabbage was sown or transplanted after the harvest of maize or other vegetables at the end of July and harvested in mid-November of the same year.

The treatments included check, no fertilizer applied (CK), fertilizer application based on yield response and agronomic efficiency (balanced OPT-NE), fertilizer application based on soil testing

(OPT-local), fertilizer application based on farmers' traditional practice (FP), and a series of nutrient omission plots, which excluded N, P, or K from the OPT-NE treatment. The treatments were arranged in random distribution. The area of each plot ranged from 15 to 30 m^2 and each treatment represented three-replicates. The fertilizer sources were urea, single superphosphate, and potassium sulphate. Urea and potassium sulphate were split applied two (basal and heading stage) or three times (basal, rosette stage, and heading stage) depending on soil fertility or expected yield responses to N and K, while single superphosphate was broadcast and incorporated as basal before seeding or transplanting. The rates of fertilizer application are listed in Table 2. Irrigation and other cultural practices were applied using the best local management.

At harvest, the cabbage in each plot was harvested manually to determine biomass yield. Cabbage samples were selected and oven-dried at 60 °C for the determination of dry matter weight, and then digested with H_2SO_4–H_2O_2 and analyzed for the determination of N concentration by the Kjeldahl method. Details for the analysis and calculation methods of total N uptake, agronomic efficiency of N (AEN), recovery efficiency of N (REN), and gross profit (the gross return above fertilizer cost) were calculated as follows:

$$\text{Total N uptake} = \text{N concentration in plant} \times \text{dry weight of Chinese cabbage} \quad (1)$$

$$\text{AEN} = (\text{yield production in full N, P, and K plot} - \text{yield production in N omission plot})/\text{N fertilizer application} \quad (2)$$

$$\text{RE} = (\text{N accumulation in plant of full N, P, and K plot} - \text{N accumulation in plant of N omission plot})/\text{N fertilizer application} \times 100\% \quad (3)$$

$$\text{Gross profit} = \text{price of cabbage} \times \text{yield production} - \text{N fertilizer cost} - P_2O_5 \text{ fertilizer cost} - K_2O \text{ fertilizer cast} - \text{organic fertilizer cost} \quad (4)$$

Data was analyzed using ANOVA with SPSS 20.0 for Windows. Mean separation between different treatments was calculated using least significant difference (LSD) at 0.05 or 0.01 level.

Table 2. The rates of fertilizer application in the validated experiments.

Province	Treatment	Fertilizer Application (kg/ha)		
		N [1]	P_2O_5 [2]	K_2O
Beijing Lichun(2018)	FP [3]	330 (1:1)	120	50 (basal)
	OPT-NE [4]	289 (2:1:1)	78	232 (2:1:1)
	OPT-local [5]	270 (1:1)	120	250 (1:1)
Beijing Zhangziying (2018)	FP	330 (1:1:1)	120	50 (basal)
	OPT-NE	278 (4:3:3)	111	314 (3:3:4)
	OPT-local	270 (1:1:1)	135	225 (1:1:1)
Hebei (2018)	FP	382 (1:1:1)	208	278 (1:1:1)
	OPT-NE	300 (5:3:2)	113	340 (4:3:3)
	OPT-local	270 (1:1.5:1)	135	210 (1:1.5:1)
Shandong (2018)	FP	90 (1:1)	90	90 (1:1)
	OPT-NE	296 (1:1)	75	169 (1:1)
	OPT-local	291 (1:1)	180	270 (1:1)
Beijing Zhangziying (2017)	FP	300 (1:1)	120	50 (basal)
	OPT-NE	270 (1:1)	90	225 (1:1)
Beijing Weizhuang (2017)	FP	300 (1:1)	120	50 (basal)
	OPT-NE	270 (1:1)	90	225 (1:1)
Beijing Shunyi (2017)	FP	300 (1:1)	120	50 (basal)
	OPT-NE	270 (1:1)	90	225 (1:1)

[1] Numbers in parentheses indicate the ratio of basal fertilizer to topdressing fertilizer; [2] Single superphosphate was broadcast and incorporated as basal before seeding or transplanting; [3] FP: Fertilizer application based on farmers' traditional practice; [4] OPT-NE: Fertilizer application based on yield response and agronomic efficiency; [5] OPT-local: Fertilizer application based on soil testing.

3. Results

3.1. Characteristics of Soil Indigenous Nutrient Supply

The soil indigenous nutrient supply can be expressed in terms of the nutrient uptake by the crop in the nutrient-omission plot (only one nutrient is omitted and other nutrients supply are sufficient), indicating the actual supply capacity of the nutrient from the soil itself [17,18]. We collected multiple-site and multiple-year datasets from published literature on Chinese cabbage and published or unpublished datasets from the International Plant Nutrition Institute, and then we selected the nutrient-omission plot for each experiment and retrieved the N (P or K) accumulation data. For example, the indigenous N supply is calculated from the value of N accumulation in plant in N omission plot, which plot had only N nutrient omitted and other nutrients sufficiently supplied. The N accumulated by plant in the N omission plot is absorbed from the soil and external environment. So, it is called the soil indigenous N supply. Ultimately, we counted the numbers of indigenous N supply value and calculated the average N nutrient supply. The same was done for indigenous P and K supply.

If the indigenous nutrient supply is high, it indicates the strong soil supply capacity to the nutrient, and the lower yield response after applying this nutrient. According to the available sample datasets, the average indigenous nutrients supply of N, P, and K were 112.98 (n = 32), 35.03 (n = 39), and 213.15 kg/ha (n = 28), respectively. It can be seen that the indigenous nutrient supply cannot be neglected when making fertilizer recommendations and needs to be fully utilized. The fertilizer recommendation of Chinese cabbage based on yield response and agronomic efficiency should make full use of the indigenous nutrients and then supplement the appropriate amount of fertilizer to achieve a higher target yield.

3.2. Characteristics of Yield Response

Yield response is the yield difference between the optimal nutrient management treatment with N, P, K fertilizer and the corresponding treatment without a certain nutrient. The yield responses to N, P_2O_5, and K_2O are shown in the Figure 1. The results showed that the yield response to N was 26.6 t/ha on average (n = 138), and there were 19.6%, 24.6%, 17.4%, 20.3%, and 18.1% of the samples distributed in the ranges of 0–10, 10–20, 20–30, 30–40, and >40 t/ha, respectively. The average yield response to P_2O_5 was 13.9 t/ha (n = 87). There were about 50.6% of the samples less than 10 t/ha, and the yield responses to P_2O_5 ranging from 10–20, 20–30, and >30 t/ha accounted for 21.8%, 16.1%, and 11.5%. The average yield response to K_2O was 16.6 t/ha (n = 253), and there were 30.8%, 40.3%, and 28.9% of the samples showing yield responses below 10 t/ha, 10–20 t/h,a and higher than 20 t/ha.

Overall, the yield response of Chinese cabbage after nitrogen application was higher than that of phosphate or potassium fertilizer, which indicated that nitrogen fertilizer was the first factor limiting the yield of Chinese cabbage. The effect of potassium fertilizer on the yield of cabbage was slightly higher than that of phosphate fertilizer.

The larger the yield response corresponding to a certain nutrient, the less the indigenous nutrient supply that can be obtained from the soil and the external environment. When the basal yield decreased, it resulted in the yield response increasing in comparison with the treatment of sufficient nutrient supply. On the contrary, if the yield response corresponding to a certain nutrient is smaller, it means that the intensity of indigenous nutrient supply is higher, and when the fertilizer is applied, the yield response is relatively small.

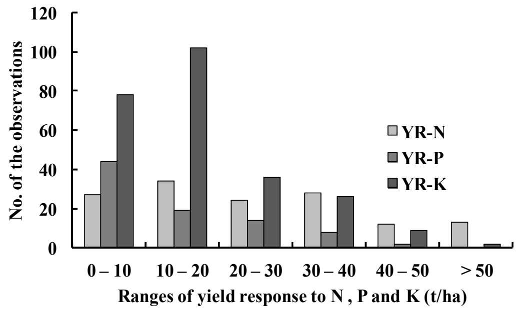

Figure 1. Frequency distribution of yield responses to applied N, P, and K fertilizer for Chinese cabbage. YR-N, YR-P and YR-K mean the yield response to N, P_2O_5, and K_2O, respectively.

3.3. Characteristics of Relative Yield

The relative yield refers to the ratio of the yield in the nutrient-deficient region to the yield in the nutrient-rich N, P, K fertilizer applied region, and to a certain extent indicates the level of the indigenous nutrient supply capacity of the soil. The larger the relative yield, the higher the indigenous supply capacity of the soil. Conversely, the smaller the relative yield, the lower the indigenous supply capacity of this nutrient in the soil.

In these collected datasets, the relative yields of N, P_2O_5, and K_2O (RYN, RYP, RYK) were 0.70 (n = 138), 0.84 (n = 87) and 0.84 (n = 248) compared with the treatments with rich N, P_2O_5, and K_2O supply, respectively, and about 23.2%, 38.4%, and 34.1% of RYN were distributed in the ranges of 0.4–0.6, 0.6–0.8, 0.8–1.0 (Figure 2). The relative yields of P_2O_5 and K_2O were mainly in the range of 0.8–1.0, accounting for 71.3% and 76.6% of the total samples, respectively. It can be seen that nitrogen fertilizer has the greatest effect on the yield increase of Chinese cabbage, and phosphate fertilizer and potassium fertilizer have almost the same effect on the yield increase. It also showed that the indigenous P and K nutrient supply from most experiments were higher than that of N in the tested soils.

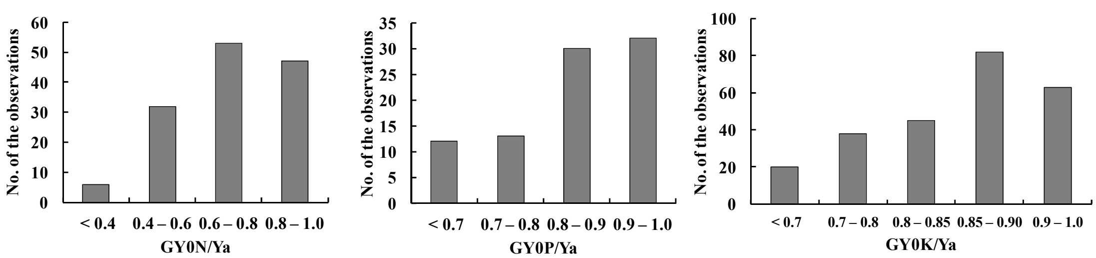

Figure 2. Frequency distribution of nutrient-limited yield to attainable yield of N, P, and K for Chinese cabbage. The relative yield "GY0N/Ya", "GY0P/Ya", and "GY0K/Ya" are the ratios between N, P, and K nutrient-limited yield and attainable yield, respectively.

3.4. Characteristics of Agronomic Efficiency

From the collected datasets, it was concluded that the agronomic efficiency of applying N, P_2O_5, and K_2O to Chinese cabbage (AEN, AEP, and AEK) were 114.3 (n = 138, ranging from 12.0 to 328.9 kg/kg), 108.5 (n = 87, ranging from 0.0 to 360.0 kg/kg), and 89.4 kg/kg (n = 253, ranging from 0.0 to 340.3 kg/kg) on average, respectively (Figure 3). From the distribution of AEN, it could be seen that about 21.0%, 31.9%, 18.8%, and 12.3% of AEN samples were distributed in the ranges of 0–50, 50–100, 100–150, and 150–200 kg/kg; about 29.8%, 24.5%, 19.1%, and 16.0% of AEP samples were distributed in the ranges of 0–50, 50–100, 100–150, and 150–200 kg/kg; about 38.5%, 26.6%, 13.1%, and 15.1% of AEK samples were distributed in the ranges of 0–50, 50–100, 100–150, and 150–200 kg/kg. Values higher than 250 kg/kg of AEN, AEP, and AEK were less distributed.

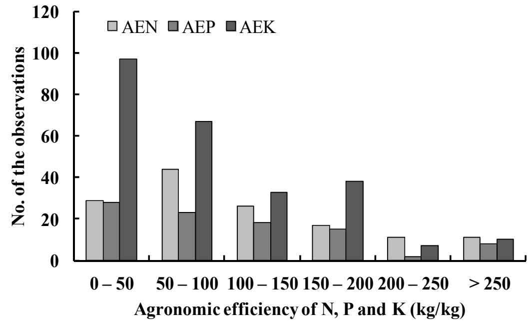

Figure 3. Frequency distribution of agronomic efficiency of N, P, and K for Chinese cabbage. AEN, the agronomic efficiency of N; AEP, the agronomic efficiency of P_2O_5; AEK, the agronomic efficiency of K_2O.

3.5. Relationship between Yield Response and Indigenous Nutrient Supply

The indigenous nutrient supply represents the actual supply capacity of the soil itself. If the indigenous nutrient supply is high, it indicates the high soil supply capacity to the nutrient, which then results in a lower yield response after the application of the nutrient. From these datasets, it was found that there was a significant negative correlation between N, P, and K indigenous nutrient supply and the yield response to N, P_2O_5, and K_2O in Chinese cabbage. The correlation coefficients *r* were 0.57 (n = 32), 0.81 (n = 39), and 0.57 (n = 28), respectively (Figure 4).

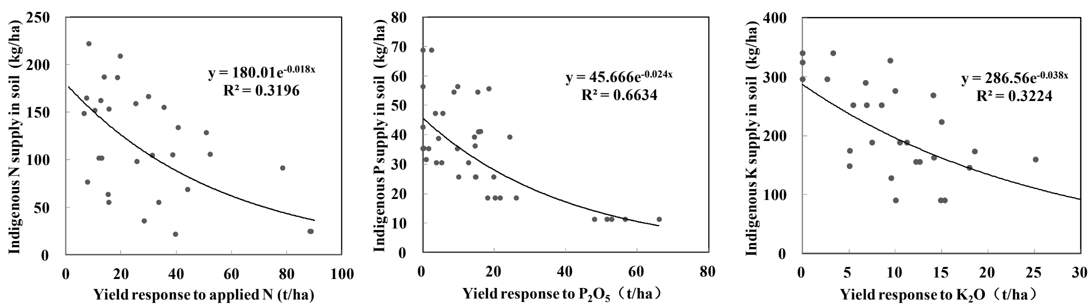

Figure 4. Relationship between yield response and soil indigenous N, P, and K supply for Chinese cabbage.

3.6. Relationship between Yield Response and Relative Yield

There was a significant negative linear correlation between yield response and the relative yield of N, P, and K in Chinese cabbage. The correlation coefficients *r* were 0.72, 0.87, and 0.74, respectively (Figure 5). The higher the relative yield, the more the indigenous nutrient supply capacity, which resulted in a lower yield increase after applying the nutrient fertilizer. Therefore, the relative yield represents the basic nutrient supply capacity of the soil, and can be used as one of the indexes to evaluate the soil nutrient supply capacity.

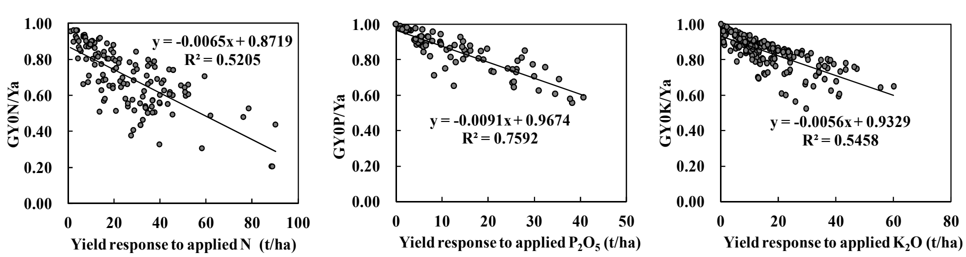

Figure 5. Relationship between yield response and relative yield for Chinese cabbage. The relative yield "GY0N/Ya", "GY0P/Ya", and "GY0K/Ya" are the ratios between N, P, and K nutrient-limited yield and attainable yield, respectively.

3.7. Relationship between Yield Response and Agronomic Efficiency

There was a significant one-dimensional quadratic function relationship between yield response and agronomic efficiency in Chinese cabbage, and the correlation coefficients reached 0.84, 0.88, and 0.84, respectively (Figure 6). The agronomic efficiency of Chinese cabbage increased with the increase of yield response, but the extent of the increase gradually decreased. The relationship between yield response and agronomic efficiency is as follows:

$$\mathrm{AEN} = -0.0138\mathrm{X}_{\mathrm{N}}^{2} + 4.4621\mathrm{X}_{\mathrm{N}} + 9.8972\ (\mathrm{R}^{2} = 0.711, \mathrm{n} = 138) \quad (5)$$

$$\mathrm{AEP} = -0.1432\mathrm{X}_{\mathrm{P}}^{2} + 9.7789\mathrm{X}_{\mathrm{P}} + 9.1813\ (\mathrm{R}^{2} = 0.775, \mathrm{n} = 87) \quad (6)$$

$$\mathrm{AEK} = -0.0242\mathrm{X}_{\mathrm{K}}^{2} + 6.3495\mathrm{X}_{\mathrm{K}} - 5.5571\ (\mathrm{R}^{2} = 0.704, \mathrm{n} = 253) \quad (7)$$

X_N, X_P and X_K were the yield responses to fertilizer N, P_2O_5, and K_2O, respectively. The relationship between yield response and agronomic efficiency can be used to recommend fertilization [19].

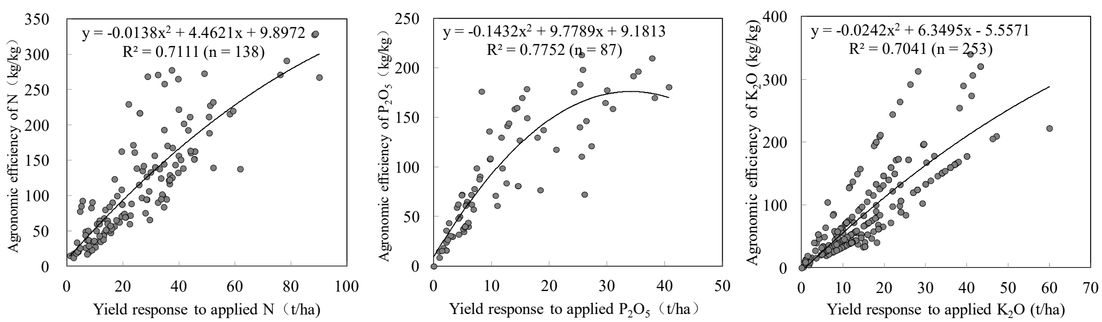

Figure 6. Relationship between yield response and agronomic efficiency of N, P, and K for Chinese cabbage.

3.8. Principles of Fertilizer Recommendation and Field Validation

From the above datasets, the theoretical basis of the recommended fertilization is established. Among the fertilizer recommendation methods for Chinese cabbage based on yield response and agronomic efficiency, the amount of nitrogen fertilizer is directly derived from the ratio of yield response and agronomy efficiency. The recommended amounts of phosphorus and potassium fertilizer are based on the initial application amount obtained by the ratio of phosphorus (or potassium) yield response and agronomic efficiency, also taking into account the amount of nutrient introduced from the crop in the last quarter and the amount of crop residues returned to the field in the current season. The application amounts of phosphorus and potassium fertilizer were corrected from the point of view of nutrient balance, and field experiments were conducted to verify it.

3.8.1. Gross Yield and Gross Profit

Field validation experiments were conducted in Beijing, Hebei, and Shandong in 2017 and 2018, respectively, to study the applicability and effect of recommended fertilization of Chinese cabbage based on yield response and agronomic efficiency. The results at the three sites of Zhangziying, Weizhuang, and Shunyi in Beijing in 2017 showed that, compared with the farmer's practice fertilization (FP treatment), OPT-NE treatment based on the yield response and agronomic efficiency reduced the application amount of nitrogen and phosphorus fertilizer, increased the application amount of potassium fertilizer, and guaranteed or increased the cabbage yield. This method avoided the environmental loss of nitrogen and phosphorus nutrients, and maintained the K nutrients in soil from being excessively consumed. The yield of Chinese cabbage treated with OPT-NE based on yield response and agronomic efficiency in three sites were 0.47, 1.11, and 26.95 t/ha higher than those treated with FP, respectively, and the yield was increased by 0.30%, 0.67%, and 27.87%. Gross profit increased by 135.94, 303.30, and 654.07 US $/ha, respectively, among which the difference of yield and gross profit between the two treatments in Shunyi reached a significant level ($p < 0.05$) (Figure 7).

In the experiments of Chinese cabbage in Beijing (Lichun and Zhangziying experiments) and Hebei Province in 2018, compared with the FP treatment, the recommended fertilization in OPT-NE based on yield response and agronomic efficiency decreased 41, 52, and 82 kg/ha of nitrogen fertilizer, 42, 9, and 95 kg/ha of phosphorus fertilizer, respectively, and increased the potassium fertilizer; the yield increased by 25.44 t/ha (11.77%) and 22.00 t/ha (16.10%) in Lichun and Zhangziying, while the yield in Hebei decreased by 3.30 t/ha. However, the gross profit in these three sites increased by 638.21 USD/ha (11.22%), 361.38 USD/ha (10.70%), and 114.44 USD/ha (3.14%). There was a significant difference in the gross profit between FP and OPT-NE treatments in the Lichun and Zhangziying experiments. Although the yield of Chinese cabbage in Hebei Province decreased slightly, the profit was still guaranteed.

In the experiment of Chinese cabbage in Shandong Province in 2018, the recommended fertilization in OPT-NE treatment based on yield response and agronomic efficiency reduced the phosphorus fertilizer by 15 kg/ha compared with FP treatment, and increased nitrogen and potassium fertilizer by 206 and 79 kg/ha, the yield increased by 3.82 t/ha, and gross profit increased by 48.91 USD/ha, which improved the yield and gross profit to a certain extent. However, it was more noteworthy that although the differences of yield and gross profit between the two treatments were not obvious in the short term, the amount of nitrogen and potassium applied by FP treatment was relatively low, and the nitrogen and potassium in the soil were exhausted. If farmers apply fertilizer habitually for a long time, there will be a downward trend in soil fertility. Therefore, based on the sustainable utilization of farmland, OPT-NE treatment properly increased the application of nitrogen fertilizer and potassium fertilizer, which is a kind of sustainable way of farmland utilization.

In the field validation experiments of Chinese cabbage in 2018, the OPT-local treatment of fertilizer recommendation based on soil testing was added to conduct a comparative study on the fertilization effect of the two methods. In terms of fertilizer application amount, the OPT-NE treatment based on yield response and agronomic efficiency would recommend fertilization according to planting information of specific plot, taking into account the interaction between nitrogen, phosphorus, and potassium nutrients, as well as the balanced input and sustainable utilization of nutrients. In the Lichun experiment in Beijing, compared with the OPT-local treatment, the OPT-NE treatment increased the nitrogen fertilizer 19 kg/ha, and decreased 42 kg/ha and 18 kg/ha of phosphorus and potassium fertilizer application. In the Zhangziying experiment in Beijing, the amounts of nitrogen applied in the two treatments were almost the same, while the amount of phosphorus applied by OPT-NE treatment decreased by 24 kg/ha, and the amount of potassium applied increased by 89 kg/ha compared to the OPT-local treatment; In the Hebei province, the OPT-NE treatment increased the nitrogen fertilizer by 30 kg/ha and potassium fertilizer by 120 kg/ha, and decreased the phosphorus fertilizer by 24 kg/ha. In the experiment of the Shandong Province, the amounts of nitrogen fertilizer used in the two treatments were almost the same, but the OPT-NE treatment reduced the amount of phosphorus fertilizer by 105 kg/ha and the amount of potassium fertilizer by 91 kg/ha.

In the end, the results showed that the yield of OPT-NE treatments in Lichun, Zhangziying, Hebei, and Shandong increased by 35.75, 9.01, 2.60, and 21.09 t/ha, and gross profit increased by 1150.20, 206.13, −59.30, and 1145.09 USD/ha, respectively, compared with OPT-local treatments. The differences of yield and gross profit between the two treatments in Lichun and Shandong experiments reached a significant level. It can be seen that the fertilizer recommendation for Chinese cabbage based on yield response and agronomic efficiency increased the yield compared with the fertilizer recommendation based on soil testing by the local agricultural technology extension department. The gross profit increased basically or even significantly, and balanced the input of nitrogen, phosphorus, and potassium nutrients and the sustainable utilization of soil. It was worth mentioning that fertilizer recommendation based on yield response and agronomic efficiency reduced time and cost compared to soil testing, which is more economical and applicable.

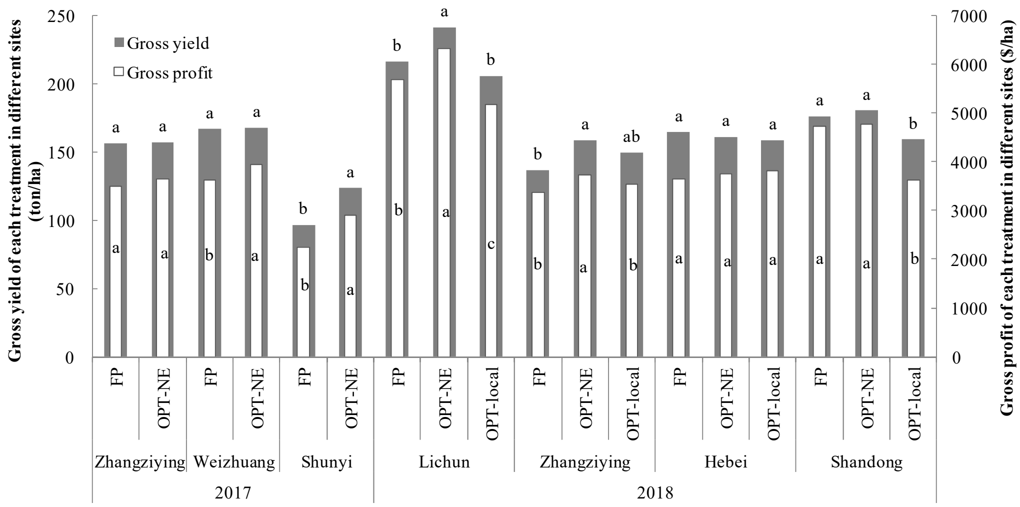

Figure 7. Gross yield and Gross profit of FP, OPT-NE, and OPT-local in different field validation experiments of Chinese cabbage. FP: Fertilizer application based on farmers' traditional practice; OPT-NE: Fertilizer application based on yield response and agronomic efficiency; OPT-local: Fertilizer application based on soil testing. USD1 = 6.88 RMB.

3.8.2. Agronomic Efficiency and Recovery Efficiency of N

The two-year field experiments showed that the average AEN of the OPT-NE treatment based on yield response and agronomic efficiency was as high as 87.85 kg/kg (Figure 8), and the average REN was 22.53% (Figure 9). In the three experiments of Lichun, Zhangziying, and Hebei, the recommended fertilization of Chinese cabbage based on yield response and agronomic efficiency not only ensured the yield, but also significantly improved the AEN and REN due to the reasonable reduction of nitrogen input. In the Shandong experiments, due to the low nitrogen fertilizer input and the depletion of nitrogen nutrient supply, the AEN and REN of OPT-NE treatment were lower than the FP treatment.

Compared with the OPT-local treatment, only the OPT-NE treatment in Hebei had lower AEN and REN value, but there was no significant difference between them. The other three experiments showed that the OPT-NE treatment had higher AEN and REN than the OPT-local treatment. It can be seen that the recommended fertilization based on yield response and agronomic efficiency of Chinese cabbage can improve the agronomic efficiency and recovery efficiency of nitrogen fertilizer, and reduce the risk of environmental loss of nitrogen to a certain extent.

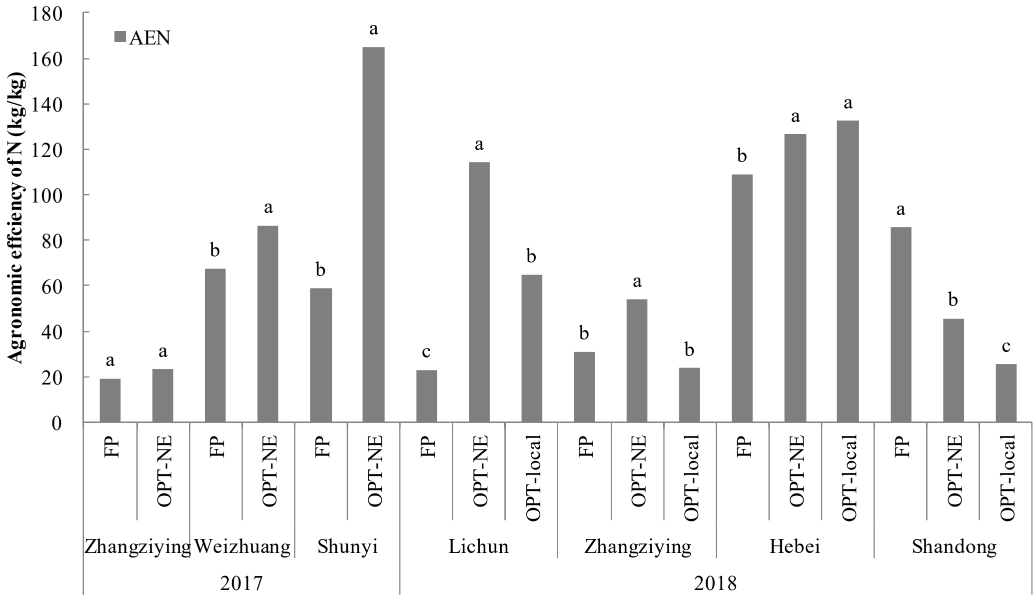

Figure 8. Agronomic efficiency of N (AEN) in FP, OPT-NE, and OPT-local treatments in different field validation experiments of Chinese cabbage. FP: Fertilizer application based on farmers' traditional practice; OPT-NE: Fertilizer application based on yield response and agronomic efficiency; OPT-local: Fertilizer application based on soil testing.

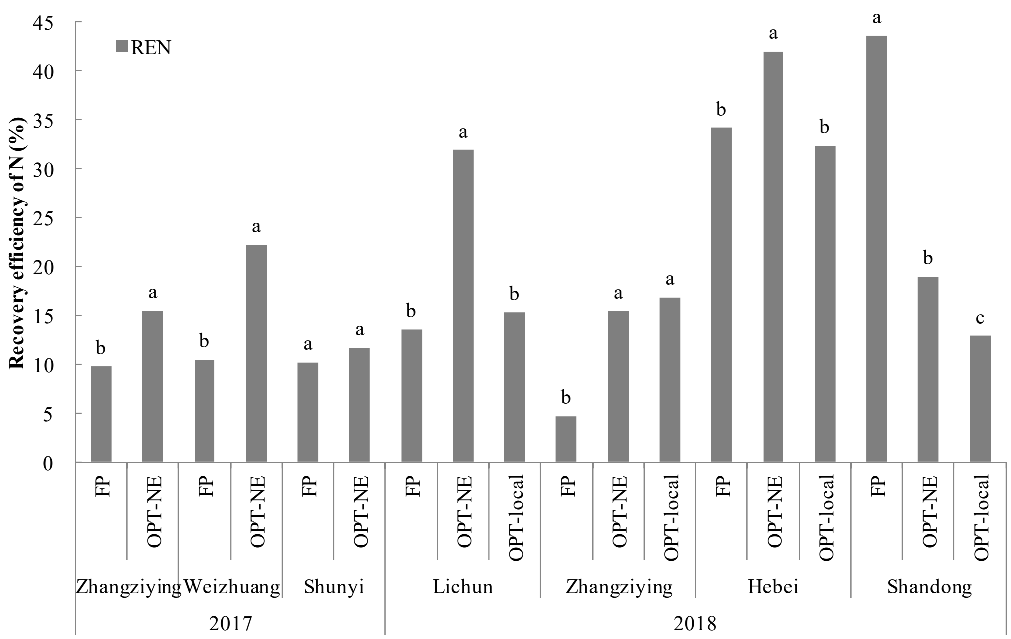

Figure 9. Recovery efficiency of N (REN) in FP, OPT-NE, and OPT-local treatments in different field validation experiments. FP: Fertilizer application based on farmers' traditional practice; OPT-NE: Fertilizer application based on yield response and agronomic efficiency; OPT-local: Fertilizer application based on soil testing.

4. Discussion

4.1. Soil Indigenous Nutrient Supply

In recent years, more and more attention has been paid to the quantitative study of soil indigenous nutrient supply. In this study, the average N, P, and K nutrient supply of Chinese cabbage in soil were 112.98, 35.03, and 213.15 kg/ha, respectively. A previous study showed that the soil indigenous nutrient supply of wheat was 122.6, 38.0, and 120.2 kg/ha in China [9], and maize was 139.9, 33.7 and 127.5 kg/ha [18], and radish was 118.7, 28.2 and 208.8 kg/ha [14], respectively. Soil indigenous nutrients are absorbed by the crops from the soil itself, including the residual effect of fertilization from the last crop and the nutrients brought by the external environment such as atmospheric deposition and irrigation water. It can be seen from the results that the indigenous nutrient supply from the soil and external environment is very high, which plays an important role in crop growth and affects the nutrient use efficiency to some extent. Jiang et al. [20] studied the impacts of potassium application rates on yield, K concentrations in grain and straw, plant K uptake, and evaluated the economic optimum K rate for maize under different levels of soil indigenous K supply. Li et al. [21] studied the yield response of nitrogen fertilizer and the optimum nitrogen fertilizer application rate for winter oilseed rape under different levels of soil indigenous N supply. It should be noted that when determining the amount of fertilizer application, the basic nutrient supply of the soil cannot be neglected, and instead, it can be used to determine a reasonable amount of fertilizer, and to create site-specific nutrient management for each crop in the field [22–25]. The recommended fertilization method of Chinese cabbage introduced in this paper considers the soil indigenous nutrient supply, combining the yield response and agronomic efficiency, also making full use of the nutrients brought by soil and external environment.

4.2. Yield Gaps for Crop

Currently researchers also focus their study on the yield gaps for crops [26–30]. There are different ways to express yield gaps, such as the yield difference between yield potential and actual nutrient management, yield difference between yield potential and optimal nutrient management, yield difference between yield potential and non-fertilization control treatment, and yield difference between yield potential and corresponding nutrient omission treatment. Yield potential can be predicted by crop growth models under no temperature or water restricted conditions. Some studies also use the maximum yield as yield potential to calculate yield gaps. However, the yield gap is easily affected by crop management measures, soil fertility, diseases, insects, weeds, and water supply, which have spatial variability. Xu et al. [31] studied the spatial variability of rice yield, yield response, relative yield, and fertilizer demand on the regional scale. Meanwhile, the spatial variability of available yield, relative yield, and fertilizer demand of maize was also studied [18,32]. These variations can reveal the spatial heterogeneity of soil nutrient supply capacity, and can be applied to make fertilizer recommendations for crops.

The yield response in this paper is the difference between the maximum yield of Chinese cabbage obtained when the nutrient supply is sufficient and the yield obtained without applying one nutrient. The recommended fertilization method for Chinese cabbage based on yield response and agronomic efficiency assumes that the basic yield of crops comes from the nutrient supply of the soil itself, and the yield gap to be increased is derived from the fertilizer. By supplementing fertilizers, the yield gap is compensated, which not only satisfies the crop production, but also avoids the loss of fertilizer resources and the risk of environmental pollution.

4.3. Methods of Fertilizer Recommendation for Crops

With the increasing demand for agricultural products in China, it is urgent to study the feasible and practical fertilizer recommendation methods to balance nutrient supply, and adopt different crop management measures, including “4R” precision nutrient management technology (right time, right type, right amount at right position), site-specific nutrient management, reasonable water and fertilizer interaction, and other technologies [33].Fertilizer recommendation based on yield response and agronomic efficiency has been studied on different crops in a number of countries around the world [6,34,35]. This method of nutrient management is simple and feasible for both large regions and small farmers, and is combined with site-specific nutrient management technology to meet the nutrient requirements of crops. A number of studies have confirmed that this method can improve crop yield, economic benefits, and fertilizer recovery efficiency, while maintaining the soil nutrient balance, ensuring the sustainable use of farmland, and showing good application prospects.

The results of this study also prove that the recommended fertilization method can reasonably guide the fertilization of Chinese cabbage, and the experimental results are worthy of affirmation. The greatest advantage is that this method overcomes the weaknesses of the process of soil testing such as soil sample collection, soil-testing results weak representative of soil fertility, long testing times, untimely recommendations and so on. It is particularly important to use when conditions such as soil testing and plant diagnosis are insufficient. This method will gradually be wide-spread in the field of agricultural production on the basis of small-scale field experiment verification, and will become a popular form of recommended fertilization technology.

5. Conclusions

In this study, multi-year and multi-site experiments were retrieved from the published literature and public scientific research institutions to study a sustainable fertilizer recommendation method for Chinese cabbage based on yield response and agronomic efficiency. The results showed that the average indigenous nutrients supply of N, P, and K were 112.98, 35.03, and 213.15 kg/ha, respectively, which cannot be neglected when make fertilizer recommendations. The average yield responses to N, P_2O_5, and K_2O were 26.6, 13.9, and 16.6 t/ha; the relative yields were 0.70, 0.84, and 0.84; also, it was concluded that the agronomic efficiencies were 114.3, 108.5, and 89.4 kg/kg on average, respectively. From these datasets, the theoretical basis of recommended fertilization was established. It was found that there was a significant negative correlation between N, P, and K indigenous nutrient supply and the yield response to N, P_2O_5, and K_2O, and a significant negative linear correlation between yield response and the relative yield of N, P_2O_5, and K_2O in Chinese cabbage. There was also a significant one-dimensional quadratic function relationship between yield response and agronomic efficiency in Chinese cabbage. Then two years of field experiments for Chinese cabbage were conducted to verify the fertilizer recommendation based on yield response and agronomic efficiency. The results showed that fertilizer recommendation of Chinese cabbage based on yield response and agronomic efficiency guaranteed or increased the yield and gross profit, also improved the agronomic efficiency and recovery efficiency, which is sustainable for farmland utilization. This method not only economically and suitably satisfies the application of recommended fertilization on fields of different sizes, but also takes into account the indigenous nutrient supply and the interaction between N, P, and K, showing the advantages of high efficiency, especially when the conditions such as soil testing and plant diagnosis are not sufficient.

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