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Effects of the Application of Organic Fertilizers on the Yield, Quality, and Soil Properties of Open-Field Chinese Cabbage (*Brassica rapa* spp. *pekinensis*) in China: A Meta-Analysis

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Abstract: With the development of sustainable agriculture, trials on the benefits of the application of organic fertilizers around the world have been conducted. Herein, we investigated the impact of the pure chemical fertilizers (CFs) combined with organic fertilizers compared with the application of CFs (100% CFs) and no fertilizers (NFs) on soil properties as well as the yield and quality of Chinese cabbage through meta-analysis. Results indicate that: (1) Compared with NFs, the application of organic fertilizers can significantly improve the yield and quality of Chinese cabbage and increase soil nutrients. (2) Compared with CFs, the application of organic fertilizers can increase the fresh weight, number of leaves, transverse diameter, leaf length, and development of Chinese cabbage per plant, with increases of 8.54%, 6.6%, 9.905%, 8.42%, and 10.03%; Meanwhile, organic fertilizers can significantly increase the yield (total amount of above-ground parts produced) and commercial yield (the portion that meets the required quality standards and is intended for sale) of Chinese cabbage to increase the yield and commercial yield by 10.08% and 35.56%, respectively. However, it has no significant impact on the income from growing Chinese cabbage. (3) Compared with CFs, the application of organic fertilizers can significantly increase the content of vitamin C (11.06%), soluble sugar (19.16%), and soluble protein (8.83%) and reduce the content of nitrate and nitrite in Chinese cabbage, with a reduction of up to 19.02% and 20.9%, respectively. The application of organic fertilizers will also have a certain impact on the absorption of heavy metals in Chinese cabbage. (4) Compared with CFs, the application of organic fertilizers can significantly improve soil organic matter, soil carbon sequestration, nitrogen absorption, and potassium absorption, showing increases of 12.73%, 13.19%, 7.91%, and 7.37%, and the application of organic fertilizers reduces soil electrical conductivity and available nitrogen, showing decreases of 36.78% and 38.75%, respectively. (5) The application of organic fertilizers significantly increased the content of soil urease and soil sucrase, increasing by 9.42% and 17.16%, respectively. This study helps inform the application of organic fertilizers in Chinese cabbage production.

Keywords: organic fertilizer; Chinese cabbage; meta-analysis; yield; quality; soil properties

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1. Introduction

With rapid socio-economic development, population growth, urban expansion, and the excessive and unplanned use of natural resources, the loads of pollutants in water and soil bodies continue to increase [1,2], thus threatening ecological sustainability and human well-being. Chemical fertilizers (CFs) provide essential nutrients (nitrogen, phosphorus, potassium, etc.) for plant growth and play an irreplaceable role in promoting agricultural development and maintaining national food security in China. However, excessive use of fertilizers causes several environmental issues, such as soil acidification, atmospheric nitrogen deposition, and water quality degradation [3,4]. In the United States, agricultural production is the main source of pollution in rivers, and 38% of water bodies in the countries of the European Union are clearly under serious threat from agricultural pollution; in China, rural non-point source pollution is also a major source of pollution in surface water bodies, seriously threatening the entire country's drinking water safety [5,6]. In China's agricultural production, excessive consumption of chemical fertilizers and a lack of organic fertilizers are important reasons for reducing crop yields and soil fertility and causing environmental pollution.

The negative effects of agricultural practices could be reversed by the optimal utilization of organic amendments (e.g., crop residues, animal manure, compost, and biochar) either alone or in combination with an optimized N fertilizer based on an improved in-season N management strategy (nitrogen inputs and nitrogen outputs for the growing season were calculated based on the fertilizer requirement pattern of the crop at different times) [7]. Organic matter in organic fertilizers can provide a variety of nutrients and energy sources for soil microorganisms, promoting microbial metabolism and activity and thereby enhancing the activity and growth rate of soil microorganisms [8]. It can also improve soil structure, enhance soil aeration and water-holding capacity, and regulate soil pH, thus creating a more favorable growth environment that benefits the survival and reproduction of soil microorganisms [9]. Meanwhile, organic matter and beneficial microorganisms in organic fertilizers have strong adsorption and chelation effects on heavy metal ions, thereby reducing the migration and enrichment of heavy metals in crops [10,11]. The properties of organic fertilizers make them have great significance in agricultural production systems.

A meta-analysis showed that in rice cropping systems, partial replacement of chemical fertilizers by organic fertilizers significantly increased the yield by 1.4–5.9%, but full replacement of chemical fertilizers by organic fertilizers significantly decreased the yield by 2.9%. The positive effects of manure substitution on yield were stronger with long-term ($\geq$10 years) fertilization because of the slow release rate of organic fertilizers. The effect of soil improvement relies on the fermentation and decomposition processes of organic fertilizers [12]. The study shows that maize yield and nitrogen (N) use efficiency tended to increase with increasing N application rates following the substitution of mineral fertilizer with organic fertilizers. At an equivalent N rate, substituting mineral fertilizer with organic fertilizers increased maize yield by 4.22% [13]. In wheat cropping systems, organic fertilization significantly increased grain yield by an average of 18% compared to plots without organic fertilizers and reduced spatial and temporal yield variability [14]. In tomato cropping systems, the application of organic fertilizers (the total) compared with 100% CFs can increase the yield by 3.48%, acidic soil (pH < 6) by 7.98%, and neutral soil (pH = 6–8) by 3.35% [15]. The application of organic fertilizers has been shown to increase yields in several cropping systems.

Chinese cabbage (*Brassica rapa* spp. *pekinensis*) has a long history and is widely cultivated in China. Chinese cabbage contains abundant vitamins, dietary fiber, and antioxidants, which can promote intestinal peristalsis and aid digestion. During the cultivation process of Chinese cabbage, certain water and fertilizer conditions (adjusting water and nutrient supply according to the growth stage) are required to ensure its yield and quality. Organic fertilizers are rich in nutrients and widely used for improving vegetable production [16]. However, resistant substances (antibiotics, heavy metals, pesticides, etc.) in organic fertilizers can enter soils and be released and transferred to the leaves of vegetable species, affecting their quality [17–20]. Specialists primarily originate (e.g., antibiotics or heavy metals) from exogenous inputs such as manure application or gene mutations by co-selection and may potentially threaten human health [21,22]. Therefore, clarifying the impact of the application of organic fertilizers on the growth, quality, and soil properties of Chinese cabbage is of great significance for sustainable agricultural development and human health. Thus, this study takes the application of organic fertilizers as the control group and the application of 100% CFs or NFs as the treatment group. Meta-analysis was used with the aim of quantifying the effect of the application of organic fertilizers on the yield and quality of Chinese cabbage as well as the response of the soil environment to the application of organic fertilizers.

2. Materials and Methods

2.1. Data Collection

This study selected the Web of Science (https://www.webofscience.com/, accessed on 1 October 2023) and China National Knowledge Infrastructure (http://www.cnki.net/, accessed on 1 October 2023) databases and searched all publicly published literature as of 1 October 2023, using Chinese cabbage and organic fertilizers as the main keywords. The main focus of the study is on the following: (1) the response of soil physical and chemical properties, including 18 indicators such as total nutrients (total nitrogen (TN), total phosphorus (TP), total potassium (TK)), available nutrients (available N, available P, and available K), effective P, alkali-hydrolyzable N, nutrient uptake (N, P, and K), soil carbon sequestration, pH, EC, organic matter, and soil enzyme activity (alkaline phosphatase, soil saccharase, soil urease); (2) the agronomic traits of Chinese cabbage (plant height, spreading degree, leaf width, leaf length, diameter, transverse diameter, number of leaves, and fresh weight per plant), quality of Chinese cabbage (amino acid, nitrite content, nitrate content, soluble protein content, soluble sugar content, and vitamin C content), element content (N, P, K, Cu, Zn, Cr, Pb, Cd, As, Hg), and yield status of Chinese cabbage, including a total of 46 indicators.

To prevent data distortion during the literature collection process, the selection of publications for data analysis must meet the following criteria: (1) studies must be conducted in the open field, not in flower pots or greenhouses; (2) the experimental site must be located in China; (3) studies must compare the control group (with the application of organic fertilizers) and the treatment group (with 100% CFs and NFs) side by side; and (4) the average (mean), standard deviation (*SD*), and sample size (n) of Chinese cabbage growth, yield attributes, and soil physicochemical properties must be reported or possibly calculated. We assumed that the *SD* was one-tenth of the mean in cases where there was no standard error (*SE*) or SD reported [23]. If the variables regarding soil physicochemical properties included more than one soil layer, only the uppermost layer was used in the present research if SEs were provided in the study.

$$SD = SE \times \sqrt{n} \tag{1}$$

Based on the above screening criteria, a total of 63 items of eligible literature were obtained (Figure S1).

We used Excel 2010 to establish a database for literature that meets the standards. During the data collection process, if the data were presented in the form of a graph, we used GetData Graph Digitizer 2.26 to extract it. If the measurement methods and units for the same indicator were different, the same indicator was accounted for according to a unified standard before being entered. The geographical distribution of the experimental sites included in the literature is shown (Figure S2).

2.2. Meta-Analysis

A random-effects approach was employed in the present study because the included primary studies could be considered a random sample among a larger number of studies. The vast majority of studies reported more than one organic fertilization treatment, resulting in multiple fertilizer treatment effect sizes within one study. RR is the Risk Ratio, ln*RR* is the natural logarithm of *RR*. If the value of ln*RR* is less than 0, it indicates a positive impact of organic fertilization on the variable. However, when ln*RR* is greater than 0, organic fertilization will have a negative effect.

The ln*RR* was estimated as follows:

$$\ln RR = \ln \frac{M_t}{M_C} = \ln M_t - \ln M_C \quad (2)$$

The variance (*V*) was calculated as follows:

$$V = \frac{SD_t^2}{n_t M_t^2} + \frac{SD_c^2}{n_c M_0^2} \quad (3)$$

where M_t and M_c represent the mean values of the treatment groups and control groups, n_t and n_c represent the sample sizes of the treatment and control groups, and SD_t and SD_c represent the *SD* values of the organic fertilization treatments and control groups, respectively.

In addition, the weighted factor (W_{ij}), weighted response ratio (RR_{++}), SEs of RR_{++} ($S(RR_{++})$), and 95% confidence intervals (95% *CIs*) were calculated as follows:

$$w_{ij} = \frac{1}{V} \quad (4)$$

$$RR_{++} = \frac{\sum_{i=1}^{m} \sum_{j=1}^{ki} w_{ij} InRR_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{ki} w_{ij}} \quad (5)$$

$$S(RR_{++}) = \frac{1}{\sqrt{\sum_{i=1}^{m} \sum_{j=1}^{ki} w_{ij}}} \quad (6)$$

$$95\%CI = RR_{++} \pm 1.96S(RR_{++}) \quad (7)$$

If the 95% confidence interval of the effect value is less than 0, it indicates a positive effect, indicating that the application of organic fertilizer can significantly increase the yield of Chinese cabbage. If the 95% confidence interval of the effect value is greater than 0, it indicates a negative effect, indicating that the application of organic fertilizer significantly reduced the yield of Chinese cabbage. If the confidence interval is 0, it indicates that the application of organic fertilizers has no significant effect on the growth and soil properties of Chinese cabbage.

Our study was conducted for the same region and crop; further, the experimental data were divided into three subgroups to attenuate the effect of publication heterogeneity on the results and to further explore the effect of the application of organic fertilizers on Chinese cabbage yield: (1) organic fertilizer types—bio-organic fertilizer (on the basis of common organic fertilizers, it was made by inoculating specific functional microorganisms or directly compounding with these microorganisms (BOF)) and common organic fertilizer (human and animal manure, plant and animal residues, compost, green manure, etc. (COF)); (2) the application level of organic fertilizers—low (<10,000 kg hm^{-2}), moderate (10,000–30,000 kg hm^{-2}), and abundant (≥30,000 kg hm^{-2}); (3) soil types—acidic (pH < 6), neutral (pH 6–8), and alkaline (pH > 8).

2.3. Mapping Software

A database was established using Excel 2010. Graphic data were extracted using GetData Graph Digitizer 2.26. Review Manager 5.4 was used to create a literature screening flowchart. Meta-analysis was conducted using Metawin3 software. The forest plot was conducted using GraphPad Prism 9. Origin 2024 was used to perform normal fitting and correlation analysis. The distribution map of the plot points was drawn using ArcMap 10.2 in ArcGIS.

3. Results

3.1. Effect of Using Organic Fertilizers on the Growth of Chinese Cabbage

The Chinese cabbage yield response to the application of organic fertilizers is shown in Figure 1. Compared with NFs, the application of organic fertilizers can significantly promote the growth of Chinese cabbage, and all growth indicators of Chinese cabbage are significantly improved under organic fertilizers treatment. Compared with the application of CFs alone, the application of organic fertilizers can increase the fresh weight, number of leaves, transverse diameter, leaf length, and development of Chinese cabbage per plant, with increases of 8.54% (95% CI: −13.22, −3.86), 6.6% (95% CI: −12.74, −0.46), 9.905% (95% CI: −12.5, −5.69), 8.42% (95% CI: −13.09, −3.74), and 10.03% (95% CI: −16.86, −3.21), respectively. The application of organic fertilizers has no significant effect on agronomic traits such as plant height, leaf width, and diameter of Chinese cabbage compared with CFs.

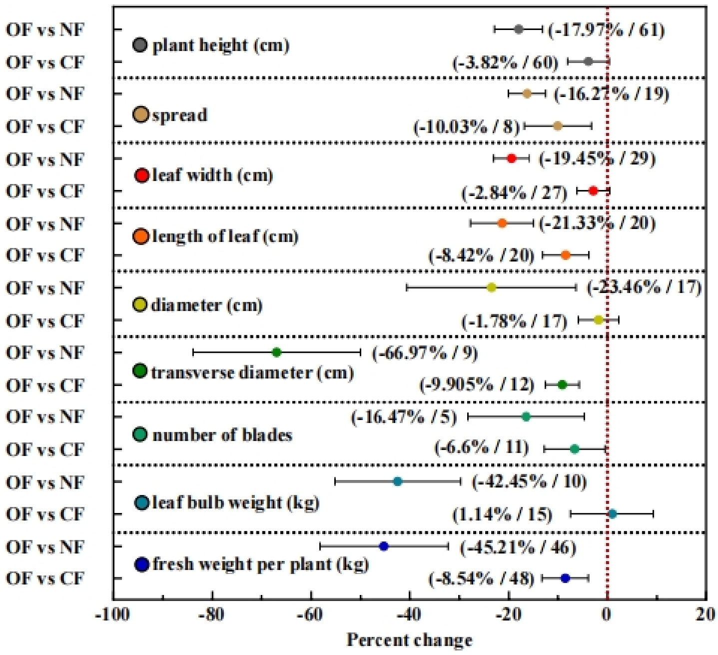

Figure 1. Effects of organic fertilizers on the growth of Chinese cabbage. The error bar represents a 95% confidence interval, and the number represents the effect value and sample size of each variable. OF: organic fertilizer; CF: chemical fertilizer; NF: no fertilizer. The red vertical line is the cutoff for positive and negative impacts, and when the 95% confidence interval contains 0, it indicates no significant impact. The different colored circles are just to distinguish different variables and have no special meaning. Same below.

3.2. Effect of Using Organic Fertilizers on the Yield and Income of Chinese Cabbage

The application of organic fertilizers has a certain impact on the yield, and the frequency of its response ratio has been fitted with a normal distribution (Figure 2; R^2 = 0.98, $p < 0.0001$). The fitting results are satisfactory, which has certain research significance. The impact of the application of organic fertilizers on the yield and income of Chinese cabbage is shown in Figure 3. Compared with NFs, using organic fertilizers can significantly increase the yield of Chinese cabbage and commercial yields, and increase profits. Compared with the application of CFs alone, the application of organic fertilizers can significantly increase the yield and commercial yield of Chinese cabbage, increasing by 10.08% (95% CI: −13.31, −6.86) and 35.56% (95% CI: −58.74, −12.38), respectively. However, it has no significant impact on the income from growing Chinese cabbage.

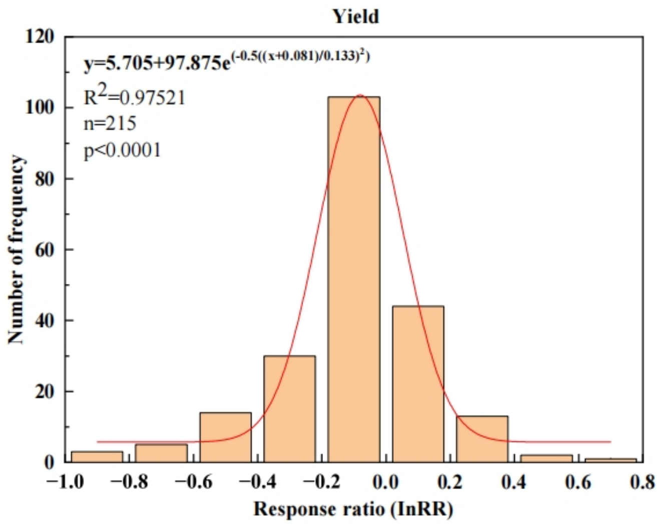

Figure 2. Chinese cabbage yield-fitting analysis. The red curve is the normal distribution fitting curve.

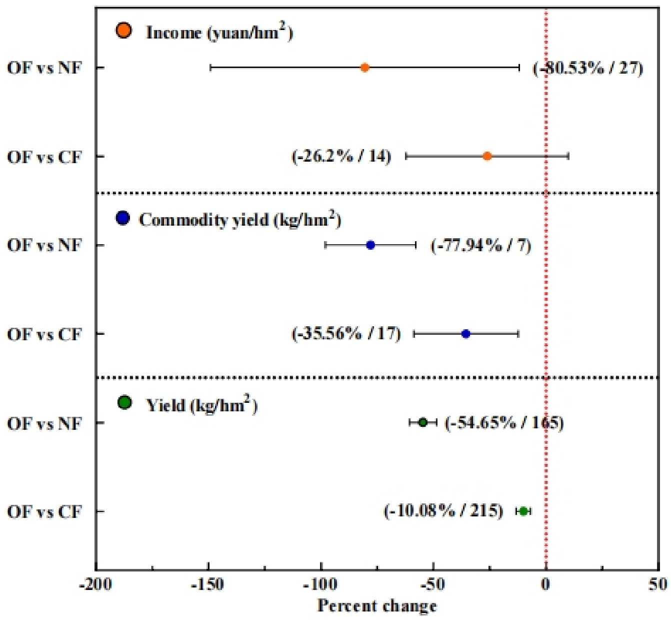

Figure 3. Effects of organic fertilizers on the yield and income of Chinese cabbage.

The yield-enhancing benefits of organic fertilizers for Chinese cabbage are closely related to the type of organic fertilizer, the amount applied, and the soil pH. The results in our subgroup analysis show that during the growth of Chinese cabbage, the application of organic fertilizers at 10,000–30,000 kg hm^{-2} has a more significant yield, increasing up to 17.71%, and there is no significant difference within the group ($p = 0.16$; Figure 4). However, the yield-enhancing effect of BOFs is not as good as that of common organic fertilizers in open-field cabbage production, and there is no significant difference between the two systems ($p = 0.15$; Figure 4). Also, our study shows that organic fertilizer substitution has the optimal yield increase of 13.03% when the soil pH value is smaller than 6. There is no significant difference in the yield increase due to organic fertilizer substitution among acidic, neutral, and alkaline soils ($p = 0.25$; Figure 4).

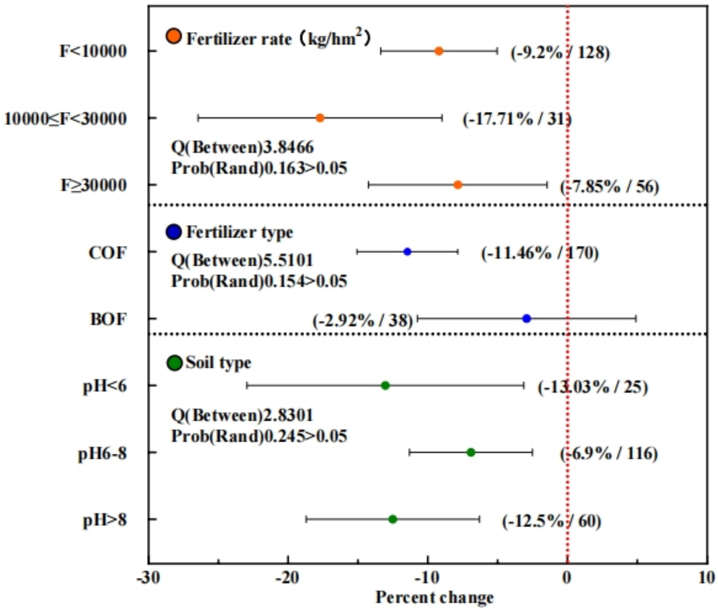

Figure 4. Subgroup analysis of the yield benefits of organic fertilizers.

3.3. Effect of Using Organic Fertilizers on the Quality of Chinese Cabbage

The application of organic fertilizers has a significant impact on the quality of Chinese cabbage (Figure 5). These results show that, compared with no fertilization or single application of CF, the application of organic fertilizers can significantly increase the content of vitamin C, soluble sugar, and soluble protein in Chinese cabbage. Among them, the increase in organic fertilizers compared with CF is 11.06% (95% CI: −15.61, −6.52), 19.16% (95% CI: −24.44, −13.88), and 8.83% (95% CI: −16.89, −12.86). Meanwhile, using organic fertilizers can significantly reduce the content of nitrate and nitrite in Chinese cabbage, with a reduction of up to 19.02% (95% CI: 16.44, 21.48) and 20.9% (95% CI: 4.55, 37.25), respectively. The application of organic fertilizers has no significant effect on its amino acid content (Figure 5).

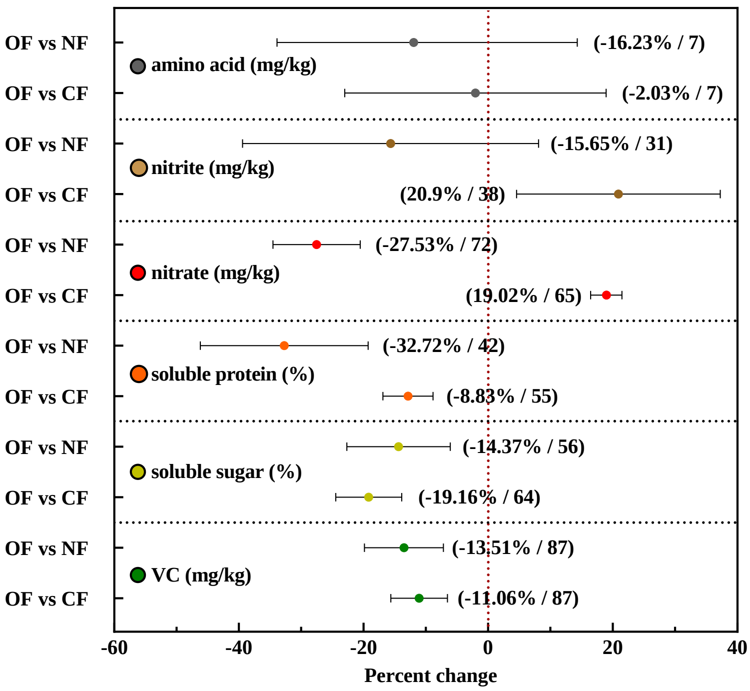

Figure 5. Effects of organic fertilizers on the quality of Chinese cabbage.

In addition, the application of organic fertilizers can affect the absorption of nutrients and heavy metals by Chinese cabbage. All in all, the application of organic fertilizers has no significant effect on the content of N, K, Cu, and As in Chinese cabbage (Figure 6). Compared with no fertilization, the application of organic fertilizers increases the absorption of Zn and Cr by 16.11% (95% CI: −28.3, −3.92) and 10.31 (95% CI: −19.81, −0.82), respectively, reducing the content of the heavy metal Pb. Compared with the application of CFs, the application of organic fertilizers can significantly reduce the P and Zn content in Chinese cabbage and reduce the heavy metal Hg content in Chinese cabbage by 26.16% (95% CI: 5.09, 47.23; Figure 6).

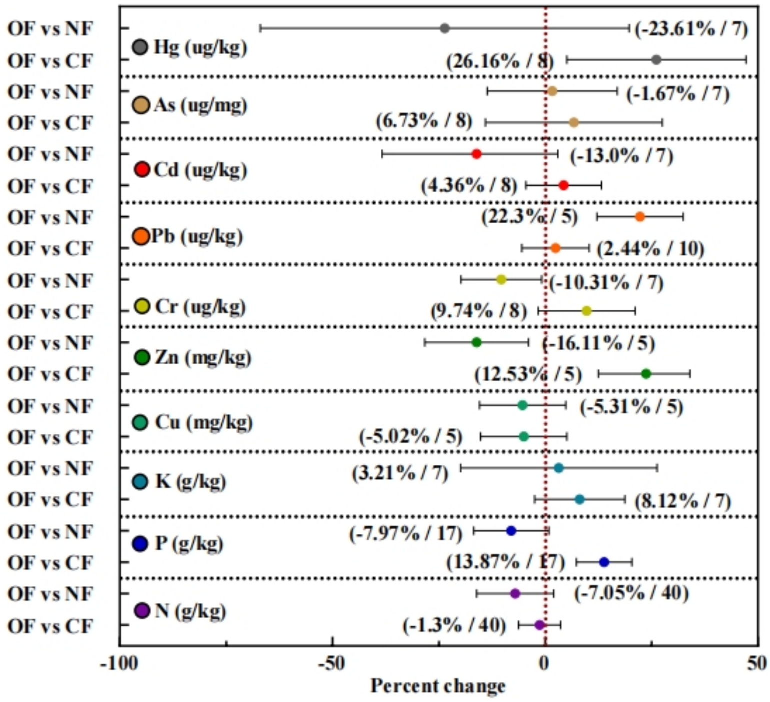

Figure 6. Effects of organic fertilizers on element absorption in Chinese cabbage.

3.4. Effect of Using Organic Fertilizers on Soil Nutrients in Chinese Cabbage Fields

Organic fertilizers are rich in nutrients, and their application can improve soil fertility traits (Figure 7). Compared with no fertilizing, the application of organic fertilizers can significantly improve soil TN, EC, organic matter, available P, available K, soil carbon sequestration, and soil N, P, and K absorption. Compared with the application of CFs, the application of organic fertilizers can significantly improve soil organic matter, soil carbon sequestration, N absorption, and K absorption, increasing by 12.73% (95% CI: −16.31, −9.61), 13.19% (95% CI: −20.01, −6.36), 7.91% (95% CI: −13.95, −1.88), and 7.37% (95% CI: −13.21, −1.53), respectively. There was no significant effect on soil TN, TP, TK, or soil pH. However, the application of organic fertilizers significantly reduces soil EC and available nitrogen, showing decreases of 36.78% (95% CI: 25.38, 48.18) and 38.75% (95% CI: 8.94, 68.56), respectively.

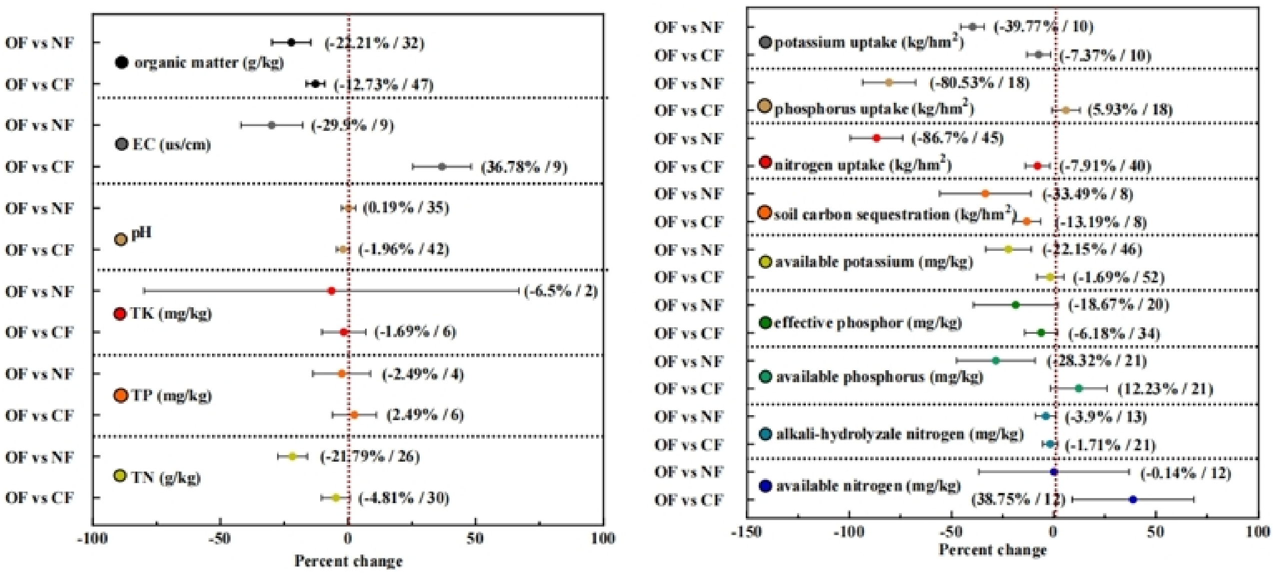

Figure 7. Effects of organic fertilizers on soil fertility.

3.5. Effect of the Application of Organic Fertilizers on Soil Enzyme Activity

The application of organic fertilizers can change the enzyme activity of soil, affecting the accumulation and release of nutrients. This study shows that, compared with no fertilization, the application of organic fertilizers can significantly increase the content of soil sucrase and soil alkaline phosphatase, increasing by 18.38% (95% CI: −50.24, −19.46) and 34.85% (95% CI: −31.00, −5.76), respectively, but has no significant effect on soil urease. Compared with the application of CFs, the application of organic fertilizers significantly increases the content of soil urease and soil sucrase by 9.42% (95% CI: −16.25, −2.6) and 17.16% (95% CI: −27.44, −6.59), respectively, but has no significant effect on soil alkaline phosphatase (Figure 8).

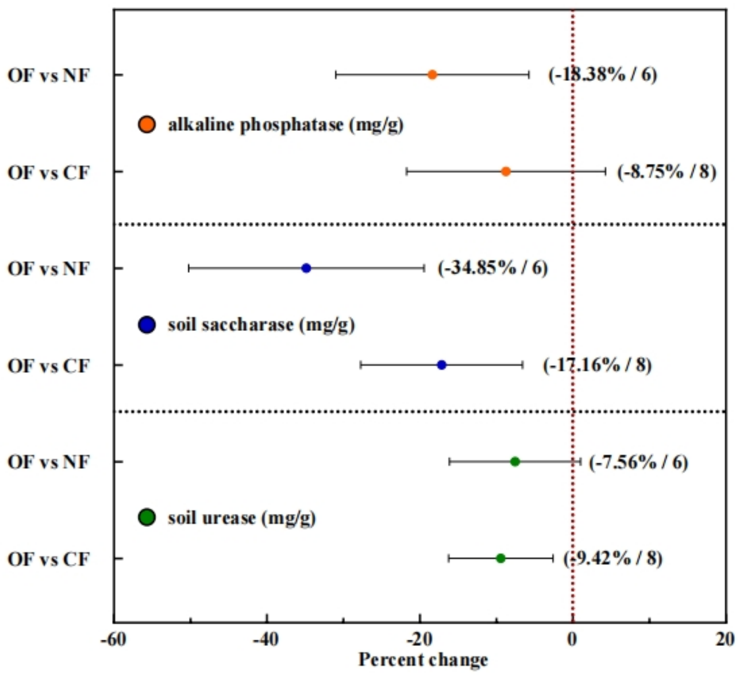

Figure 8. Effects of organic fertilizers on soil enzyme activity.

4. Discussion

4.1. Chinese Cabbage Yield Response to Organic Fertilizers Management

The application of organic fertilizers can increase Chinese cabbage yield (Figure 3). In agricultural production systems, numerous factors influence the effectiveness of organic fertilizers, including soil types, organic fertilizer types, and amounts of organic fertilizers applied. The study showed that the total substitution of organic fertilizers for CFs has limitations in improving water productivity, but the partial substitution of organic fertilizers (50%) has great potential in maintaining a high grain yield (of wheat) and improving water productivity. This may be because the improvement in soil hydraulic properties caused by total manure substitution is not enough to offset the increase in soil evaporation caused by the decrease in surface biomass cover [24]. It has also been suggested that partial organic substitution for CFs, especially 45% substitution, would be a feasible fertilization strategy to improve soil fertility and crop productivity while mitigating N_2O emissions in wheat–maize rotation systems [25]. Another study showed that a 30% substitution of inorganic nitrogen fertilizer with a plant-based organic fertilizer treatment enhanced the grain yield and anthocyanin content of colored rice by increasing nitrogen use efficiency [26]. Our study shows that the optimal application of organic fertilizers in the Chinese cabbage production system is 10,000–30,000 kg/hm^2, at which time it can increase the yield by 17.71% (Figure 4). Organic fertilizer application rates are higher in staple food production systems, and it is relevant to accurately quantify their use in vegetable production.

BOFs contain beneficial bacterial species that improve the properties of the rhizosphere soil by mediating plant–soil–root microbial interactions, thus promoting crop growth [27]. One early study suggested that the combined application of BOFs with CFs can reduce the use of inorganic fertilizers by as much as 25% [28]. Another study showed that after 30 days of a pot experiment, BOFs efficiently improved plant height and biomass (1.20- and 1.93-fold, respectively), as well as significantly increased the soil available K and pH value [29]. However, our study showed that the yield-enhancing benefits of COF were superior to those of BOFs, and our hypothesis was that the growth cycle of Chinese cabbage was shorter and the advantages of functional microorganisms in BOF were not demonstrated (Figure 4). The current study has highlighted the positive impacts of BOFs on plant adaptability and phytoremediation efficiency, with an emphasis on the optimization of rhizosphere soil properties, especially the reassembly of the soil microbiome [30]. It is also particularly relevant to clarifying the yield advantages of BOF applications.

Animal manure and crop straw soil treatments have been shown to ameliorate soil acidity [31]. The relationship between organic fertilizers and soil acidity and alkalinity is complex. Long-term application of organic fertilizers can change the soil acidity and alkalinity, and soil acidity and alkalinity can affect the organic fertilizer nutrient conversion and release. The initial soil pH, mean annual precipitation, and climate zone are the key factors affecting soil pH in the vegetable field, and their total contribution ratio to soil pH change accounted for 32.1% of all variables. When the initial soil pH is ≤ 6, the soil pH increases with the increase in substitution ratio; conversely, when the initial soil pH is >8, all substitution ratios decrease the soil pH value [32]. The yield benefits of the substitution of organic fertilizers also show differences across soil types. It is evident that the effects of different organic fertilizer types, substitution ratios, and soil types on crop yield are different, and factors such as soil type and pH should be comprehensively considered [33,34]. Additionally, we analyzed the correlation between Chinese cabbage yield and soil TN, pH, and soil organic matter after planting. Further, the results revealed that cabbage yield was positively correlated with post-harvest soil TN and pH and negatively correlated with soil organic matter, and the relationships with all three indicators were not significant ($p = 0.14$, $p = 0.37$, $p = -0.44$; Figure 9).

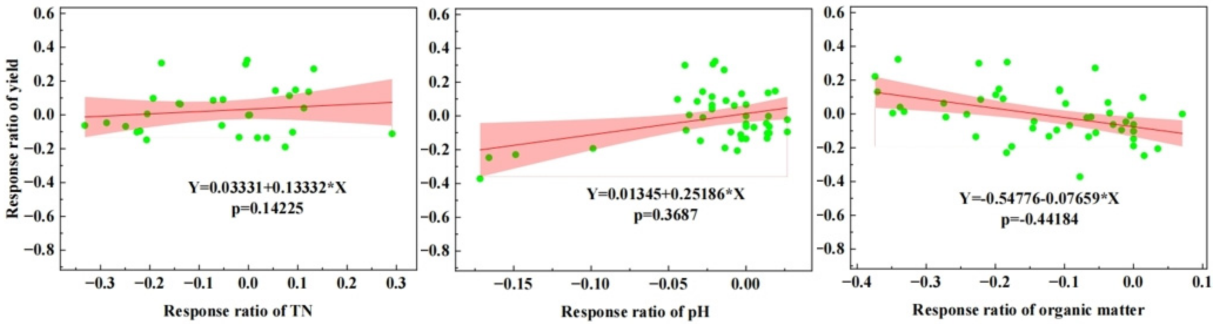

Figure 9. Correlation analysis between the response ratio of Chinese cabbage yield and total nitrogen, pH, and organic matter. The red lines and pink shaded areas are the means and 95% CIs of the slopes across all data.

4.2. Response of Chinese Cabbage Quality to Organic Fertilizer Management

Organic matter and trace elements in organic fertilizers can promote the metabolism, growth, and development of crops and improve their nutritional value. Toishimanov et al. showed that the application of organic fertilizers improved the content of fat, protein, fiber, and starch in maize by 35%, 22%, 14%, and 8%, respectively, and in soybean, the content of fat, protein, and fiber were improved by 20%, 3%, and 11% [35]. Another study also revealed that the combined application could enhance pecan quality, with the pecan kernel oil and unsaturated fatty acid contents reaching 72.33% and 97.54%, respectively [36]. An organic fertilizer substitution experiment conducted on heavy metal-contaminated land showed that biochar and organic fertilizers drive the bacterial community to improve the quality of *Sophora tonkinensis* [37]. Identifying a fertilization strategy is vital for improving the poor properties and weak fertility of newly reclaimed land. The results indicated that, compared with the application of a single-compound fertilizer, the application of BOFs significantly enhanced the dry matter accumulation of Chinese small cabbage [38]. Our study shows that the application of organic fertilizers can significantly increase the content of vitamin C, soluble sugar, and soluble protein. At the same time, it was found that the content of nitrate and nitrite in Chinese cabbage was reduced (Figure 5). Overall, the application of organic fertilizers helps increase farmers' income and promotes sustainable agricultural development.

Manure has been considered a source of heavy metal (HM) pollution in the soil. Previous research showed that there was an accumulating tendency for Cu, Zn, and Pb in paddy fields, Cu and As in orchard fields, and Zn, As, and Pb in vegetable fields [39]. The increase in HM content in soil can also affect the macronutrient, micronutrient, and HM contents of crops, posing potential risks to human health [40,41]. Increasing the application dosage of manure fertilizer undoubtedly increased the input of HMs into soils, but whether it will contribute to the long-term accumulation of HMs in the soil should still be assessed. In addition, planting crops could also take up HMs and remove them from soils. Our results indicate that, compared with the application of CFs, the application of organic fertilizers can significantly reduce the P and Zn content and reduce the heavy metal Hg content in Chinese cabbage by 26.16%, but it has no significant impact on the content of other heavy metal elements (Figure 6). Our meta-analysis results indicate that the application of organic fertilizers could be an acceptable method for ensuring soil and human health in the Chinese cabbage growing system.

4.3. Soil Effect of Organic Fertilizers

Soil quality is a key factor in improving crop productivity, contributing to soil health and sustainable production. Previous studies showed that manure fertilizer substitution significantly enhanced soil nutrients (SOC, TN, soil available P, and available K) and improved physical properties [42–44]. Coincidentally, our research shows that, compared with the application of CFs, the application of organic fertilizers can significantly improve soil organic matter, soil carbon sequestration, and N and K absorption (Figure 7). In addition, organic fertilizers increase soil water-holding capacity and particle stability, which can reduce soil bulk density and increase soil porosity [45]. Unfortunately, there is limited research on the effects of organic fertilizers on soil structure changes in vegetable fields, and our meta-analysis did not involve these indicators. A slower nutrient release rate of manure fertilizer maintains the synchronization of nitrogen supply and plant nitrogen requirements at the later growth period and reduces mineral nitrogen loss [46–48]. Soil N concentration is the primary factor responsible for cumulative pollutant emissions [49,50]. Currently, there are fewer studies examining gas emissions and nutrient losses in cabbage fields. The reason for this is that gas emissions and nutrient losses are influenced by conditions such as the types and application methods of fertilizers and rainfall [51,52].

Soil enzymes play a relevant role in soil nutrient cycling and metabolism and have a direct impact on soil fertility [53,54]. Organic fertilizers directly or indirectly increase soil humus content by promoting crop growth, thus increasing protective sites for soil enzymes and carbon and nitrogen sources for soil microorganisms, and increase enzyme activity while promoting microbial reproduction [55]. An early study showed that farmyard manure and mineral fertilizers have both positive and negative effects on soil enzymes [56], indicating that the activity of different soil enzymes depends on the enzyme types and the distribution in the particle size fraction [57,58].

5. Conclusions

Our study shows that fertilizer (CFs and OFs) application is necessary to increase yield and income in open-field Chinese cabbage production. Compared with 100% CFs, organic fertilizer dosing can promote Chinese cabbage growth, increase yield, and have a certain effect on Chinese cabbage quality. In the Chinese cabbage production, the optimal application of organic fertilizers is 10,000–30,000 kg hm^{-2}, and the yield of Chinese cabbage increases by 17.71%. Organic fertilizer types, soil acidity, and alkalinity have no significant effect on the yield benefits of organic fertilizers. In addition, our study finds that organic fertilizer can enhance soil organic matter content and increase soil enzyme activity, which is an effective measure to fertilize the soil. Our results provide a scientific basis for the further development of integrated optimization methods to take advantage of organic fertilizers and improve Chinese cabbage yield and quality. In the future, we should focus on the study of the application rate of organic fertilizers and the mechanism of the yield increase.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14112555/s1.

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