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Trait Performance Differences and Fertilizer Strategy Optimization in Cabbage Under Organic vs. Conventional Fertilization Regimes

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Abstract Nowadays, people are paying more and more attention to sustainable agriculture. The application effects of organic fertilizers and conventional chemical fertilizers in cabbage cultivation have also attracted a lot of attention. Many studies have found that these two fertilization methods can affect the yield, quality, disease resistance and resource utilization efficiency of cabbage. This study sorted out the performance of cabbage under different fertilization methods, compared the differences between organic fertilization and conventional fertilization in soil ecology, nutrient supply and crop trait regulation, and explored the possibility of combining organic and chemical fertilizers to see if this compound fertilization method can not only ensure high yields but also reduce environmental harm. This study hopes to provide some theoretical references and practical suggestions for the fertilization management of cabbage and help farmers grow more green and healthy vegetables.

Keywords Cabbage; Organic fertilization; Conventional fertilization; Nutrient management; Sustainable agriculture

1 Introduction

Fertilization is very important for increasing the yield and quality of cabbage. As long as the nutrients are managed properly, not only can cabbage grow well and have a high yield, but also its nutritional content and appearance can be improved (Cui et al., 2022; Rempelos et al., 2023) The application of organic fertilizer and bio-organic fertilizer has been confirmed by many studies to increase the fresh weight and leaf count of cabbage, as well as the content of vitamin C, sugar and protein. Meanwhile, it can also reduce the accumulation of nitrates and nitrites, allowing for more organic matter and active microorganisms in the soil (Qi et al., 2021; Qi et al., 2022; Singh et al., 2023). In addition, fertilization methods can also affect soil fertility, the carbon-nitrogen cycle, and the types of microorganisms, thereby indirectly influencing the growth and quality of cabbage (Jin et al., 2022; Wang et al., 2024; Zhang et al., 2024).

Nowadays, organic fertilization is becoming increasingly popular because it is good for the environment, can improve crop quality and soil quality. However, in pursuit of high yields, chemical fertilizers are still widely used (Kavaliauskaitė et al., 2023). Research has found that organic fertilizers can increase the content of beneficial substances such as phenols, carotenoids and vitamin C in cabbage, and also reduce the accumulation of heavy metals such as cadmium and nickel. But sometimes, the use of chemical fertilizers can lead to higher yields and more nutrients (Rempelos et al., 2023; Yfantopoulos et al., 2024). So when choosing a fertilization method, people often need to strike a balance among yield, quality, environmental impact and cost (Belay, 2021; Adhikari et al., 2023).

This study summarized and compared the different performances of organic fertilizers and chemical fertilizers in cabbage cultivation, and analyzed their roles in yield, quality, soil health and environmental impact. This study aims to provide references for how to apply fertilizers more scientifically in cabbage cultivation and how to achieve green agriculture.

2 Organic and Conventional Fertilization Systems

2.1 Characteristics of organic fertilization: sources, nutrient release, soil interaction

Organic fertilization mainly uses natural materials such as animal and plant residues, compost, manure and green manure. These fertilizers release nutrients slowly and can also interact with organic matter in the soil. Organic

fertilizer can increase the organic carbon in the soil, help the soil form aggregate structure, make the soil more water-retaining, have more types of microorganisms, and the soil as a whole becomes healthier (Chatzistathis et al., 2021; Khan et al., 2024). However, the nitrogen in organic fertilizer is released slowly and cannot immediately meet the needs during the vigorous growth period of crops, but it is very helpful for improving the long-term fertility of the soil.

2.2 Characteristics of conventional fertilization: formulation, solubility, response speed

Conventional fertilizers are mainly chemically synthesized, with clear nutrient components, dissolve quickly and be absorbed by crops very soon. The advantage of conventional fertilizers is that nutrients come quickly and can significantly increase yield. They are particularly suitable for crops that pursue high yield or have a short growth period (Knapp et al., 2023; Abd-Elmoniem et al., 2025). However, if conventional fertilizers are used in large quantities for a long time, the organic matter in the soil will decrease, the types of microorganisms will also decrease, and the soil structure is prone to be damaged (Figure 1) (Khan et al., 2024).

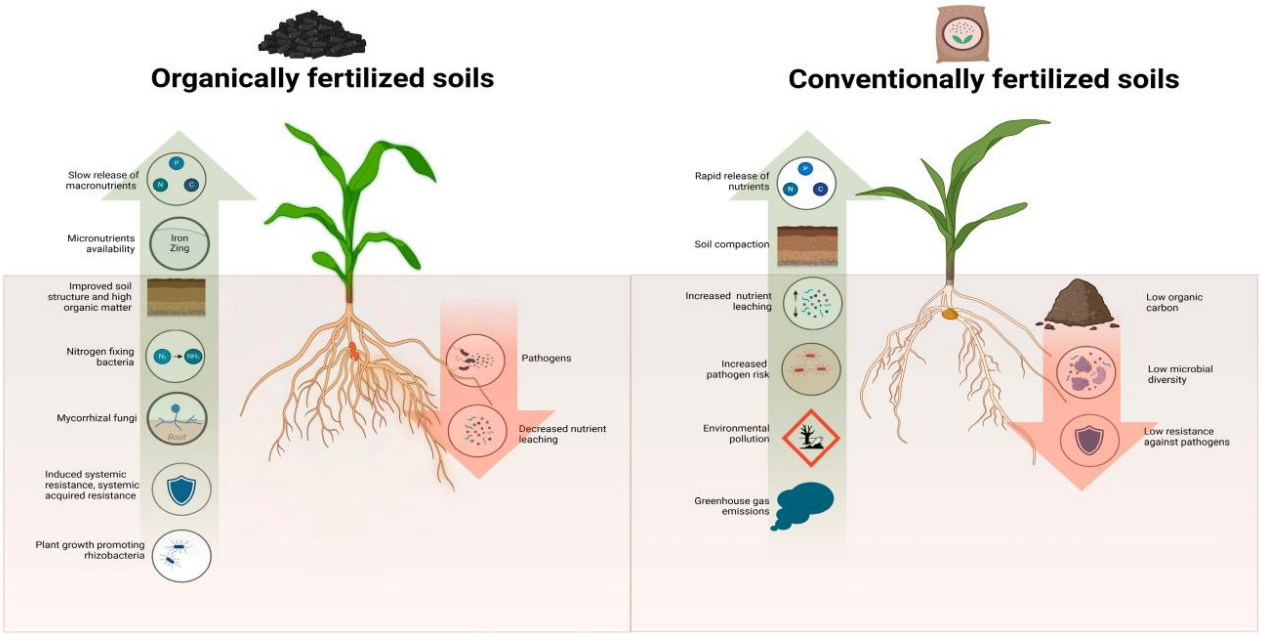

Figure 1 Comparison of organic and conventional fertilizers for soil fertilization (Adopted from Khan et al., 2024)

Image caption: Organic fertilizers provide a sustainable and steady supply of nutrients. Moreover, they offer gradual but sustainable soil health improvement that exhibits resilience against extreme climatic events. Conventional fertilizers, on the other hand, result in nutrient leaching and degrade soil quality over time (Adopted from Khan et al., 2024)

2.3 Nutrient availability, synchronization with plant demand, and environmental impact

The nutrient release rate of organic fertilizer is slow and it is not very likely to match the nutrient requirement rhythm of crops. It is prone to nutrient deficiency in the early stage, but it is beneficial for improving soil nutrient reserve and vitality (Chatzistathis et al., 2021). Chemical fertilizers can replenish nutrients in a timely manner when crops grow rapidly, but they may lead to problems such as nitrogen loss and water pollution, such as nitrate leaching and water eutrophication. Organic farming generally has a higher nitrogen utilization rate, a lower nitrogen surplus, and less pressure on the environment (Chmelíková et al., 2021; Boschiero et al., 2023).

2.4 Regulatory and certification implications in both systems

Organic farming must comply with the strict regulations of organic agriculture. Chemical fertilizers and pesticides cannot be used, and ecological circulation and sustainable development should also be emphasized. Conventional fertilization is carried out in accordance with national or regional standards, with an emphasis on fertilizer safety and environmental control (Chatzistathis et al., 2021; Khan et al., 2024). Organic systems have higher requirements for fertilizer sources, application methods and environmental impact, and will also affect whether agricultural products can enter the market and whether the selling price can be higher.

3 Trait Performance in Cabbage under Different Fertilization Regimes

3.1 Vegetative growth traits: plant height, leaf area, root development

Applying organic fertilizer can make cabbages grow better. For instance, the plant height, leaf length, leaf number and transverse diameter of cabbage treated with organic fertilizer increased by 8.54%, 8.42%, 6.6% and 9.91% respectively (Zhang et al., 2024). Fertilizers like compost and vermicompost can help root systems and above-ground parts grow faster. Among them, the effect of vermicompost is particularly obvious (Adhikari et al., 2023; Singh et al., 2023).

3.2 Yield traits: head size, marketable weight, total biomass

The use of organic fertilizers or a combination of organic and chemical fertilizers can increase the weight of cabbage heads, the yield that can be sold and the total output. Compared with chemical fertilizers alone, organic fertilizers can increase the fresh weight of cabbage by 10.08% and the commercial yield by 35.56% (Zhang et al., 2024). Some studies have found that after being treated with vermicompost, the heaviest balls formed can reach 1026 grams. When organic and chemical fertilizers are used together (like the IPNS model), the maximum yield can reach 65.0 tons per hectare (Coulibaly et al., 2021; Cui et al., 2022; Singh et al., 2023). In addition, the use of bio-organic fertilizer combined with a reduction in nitrogen fertilizer can also increase yield and root activity (Figure 2) (Qi et al., 2021; Jin et al., 2022; Qi et al., 2022).

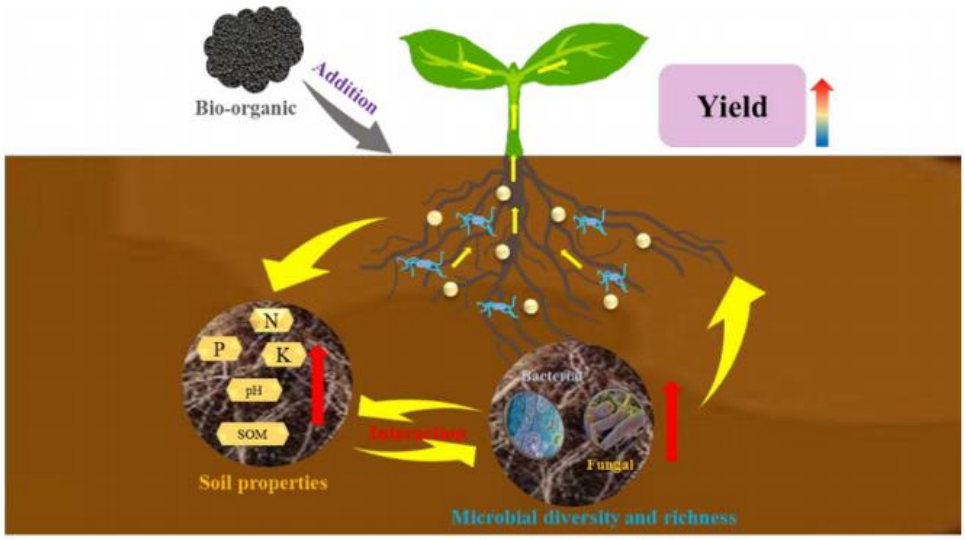

Figure 2 A model of soil physical and chemical properties, microbial community, and yield changes after adding bio-organic fertilizer (Adopted from Jin et al., 2022)

3.3 Quality traits: vitamin C, dry matter, flavor, nitrate content

Organic fertilizer can also make cabbage more nutritious. For instance, it can increase the contents of vitamin C, soluble sugar and soluble protein by 11.06%, 19.16% and 8.83% respectively (Singh et al., 2023). Meanwhile, organic fertilizer can also reduce the accumulation of nitrate and nitrite, with the reduction rates reaching 19.02% and 20.9% respectively (Qi et al., 2021; Wang et al., 2024; Zhang et al., 2024). Under organic management, cabbage has higher levels of phenols, glucosides and carotenoids, lower levels of heavy metals such as cadmium (Cd) and nickel (Ni), and better taste and safety (Rempelos et al., 2023).

3.4 Differences in maturation timing and harvest window

There is not much comparative data on when cabbage ripens and is harvested, but organic fertilizer generally can make the plants grow more evenly. Some studies have also found that the combined use of organic fertilizer and chemical fertilizer can make cabbage mature faster and have a longer harvest period, which is beneficial to field management (Cui et al., 2022). In addition, organic fertilizer can also improve soil structure and microbial environment, which is conducive to the uniform ripening of cabbage (Qi et al., 2022; Singh et al., 2023).

4 Soil Health, Nutrient Cycling, and Microbiological Interactions

4.1 Effects on soil structure, organic matter content, and moisture retention

After the application of organic fertilizer, the organic matter in the soil increased, the water retention capacity was stronger, and the structure was more stable (Luan et al., 2023). It can also reduce the salinity (electrical conductivity) of the soil, making the basic condition of the soil better (Zhang et al., 2024). Compared with using only chemical fertilizers, using organic fertilizers or a combination of organic fertilizers and chemical fertilizers can increase the useful nutrients such as organic matter, phosphorus and potassium in the soil, and also increase the enzyme activities in the soil, such as urease and sucrase. This is very helpful for maintaining the long-term health of the soil (Li et al., 2023).

4.2 Rhizosphere microbial diversity and functional roles

The use of organic fertilizer or bio-organic fertilizer can also enrich the microorganisms in the soil, especially for beneficial bacterial communities such as fungi and bacteria, their quantity and activity level will increase (Li et al., 2024). These microorganisms can help plants absorb nutrients, reduce diseases, and promote better growth of crops (Gao et al., 2023; Wang et al., 2023). Organic fertilizer can also regulate the microbial structure in the soil, making the soil more drought-resistant and stable (Jin et al., 2022; Lee et al., 2025).

4.3 Nutrient cycling efficiency and long-term soil fertility trends

Organic fertilizer or its combination with chemical fertilizer can make nutrients such as nitrogen, phosphorus and potassium in the soil more easily absorbed by plants (Hu et al., 2022). Organic fertilizer can also enhance the activity of soil enzymes, enabling nutrients in the soil to decompose faster and be utilized more fully (Luan et al., 2023). Compared with chemical fertilizers alone, organic fertilizers can better maintain the balance of soil nutrients, reduce loss, and also increase the yield and quality of crops (Sarkar et al., 2021).

4.4 Fertilizer residues and their legacy effects

Organic fertilizers can also reduce the contents of nitrates, nitrites and heavy metals (such as cadmium and nickel) in cabbage and soil, thereby reducing the risks to the environment and food safety. Conversely, if chemical fertilizers are used continuously, these harmful substances may accumulate gradually in the soil and crops, bringing some hidden dangers (Rempelos et al., 2023; Zhang et al., 2024). So in the long term, the use of organic fertilizers is more conducive to improving the soil environment and reducing the problems caused by fertilizer residues.

5 Fertilizer Use Efficiency and Environmental Sustainability

5.1 Nitrogen use efficiency (NUE) and loss pathways in each system

Controlling the amount of nitrogen fertilizer properly is the key to increasing the yield of cabbage and the nitrogen use efficiency (NUE). There are many new fertilization methods, such as organic fertilizers, slow-release fertilizers, biochar fertilizers, and bio-bacterial agents, all of which can significantly increase NUE. For instance, some studies have found that replacing part of the chemical fertilizer with 30% organic fertilizer can increase NUE by 55.6% to 97% (Cui et al., 2022). After the application of biochar slow-release fertilizer, the efficiency of nitrogen absorption by crops is higher and the yield can also increase (Zhao et al., 2022). In addition, when using a moderate amount of biogas liquid fertilizer, such as DF-170, the NUE can even be more than twice as high as that of chemical fertilizers. However, if too much is used, it may instead reduce NUE and also cause the loss of ammonia volatilization (Jin et al., 2022). Another approach is to use biological agents together with a reduction in chemical fertilizers, which can also improve both NUE and yield (Sarkar et al., 2021).

5.2 Risk of nutrient leaching and runoff

Long-term and excessive application of chemical fertilizers can easily lead to excessive inorganic nitrogen residue in the soil, and thus nitrogen is more likely to flow away with rainwater (Cao et al., 2023). The use of organic fertilizers and slow-release fertilizers can reduce this problem. They can lower the electrical conductivity of the soil and the active content of nitrogen, thereby reducing nitrogen loss (Sikora et al., 2020). Organic fertilizer can also improve soil structure, increase organic matter, and allow nitrogen to be retained for a longer time. It is also beneficial for preventing soil salinization (Jin et al., 2022; Zhang et al., 2024). In addition, using biochar fertilizer or liquid organic fertilizer can also reduce fertilizer loss and be more environmentally friendly (Zhao et al., 2022).

5.3 Greenhouse gas emissions and carbon footprint comparison

Slow-release fertilizers and organic fertilizers can also help reduce greenhouse gas emissions. For instance, under a reasonable nitrogen dosage, slow-release fertilizers can reduce greenhouse gas emissions per kilogram of cabbage by 30%, and emissions related to fertilizers can also be reduced by half (Sikora et al., 2020). Organic fertilizers and biochar fertilizers can also enhance the carbon storage capacity of soil, and less use of chemical fertilizers can also reduce overall carbon emissions (Zhao et al., 2022). Less application of chemical fertilizers can also reduce the nitrogen footprint and lower the social and environmental costs. When growing vegetables, it can even reduce the nitrogen footprint by 29% to 61%.

5.4 Indicators of environmental performance

According to life cycle assessment (LCA), if combined with reasonable fertilization and covering measures, it can also reduce water consumption, land area and environmental toxicity (Ponjičan et al., 2021). Organic fertilizers and slow-release fertilizers not only increase the yield and quality of cabbage, but also enhance the enzyme activity and carbon storage capacity in the soil, which is also beneficial to the ecological environment (Sarkar et al., 2021). In addition, with customized nutrient management systems (such as NEc), it is possible to increase the yield while making the fertilizer utilization rate higher and more environmentally friendly (Liu et al., 2025).

6 Optimization Strategies for Fertilizer Application in Cabbage

6.1 Timing and frequency of application

To make cabbage grow better and apply fertilizer more efficiently, the key is to arrange the timing and frequency of fertilization properly. Research has found that applying nitrogen, phosphorus and potassium in stages during the seedling stage and the mature stage, for example, using 210 kilograms of nitrogen, 105 kilograms of phosphorus and 210 kilograms of potassium per hectare, can greatly improve fertilizer utilization rate and also increase yield (Cao et al., 2023; Liu et al., 2025). Applying the fertilizer in several portions, from the side or by drip irrigation can also help reduce fertilizer loss and allow cabbage to absorb it more fully (Coolong et al., 2022).

6.2 Methods: banding, foliar feeding, fertigation, compost integration

The methods of fertilization have different effects on the growth of cabbage. Strip fertilization and multiple toppings of liquid fertilizer can reduce nitrogen loss and enable cabbage to grow better in the early stage (Coolong et al., 2022). During critical growth periods, such as the rapid growth period, foliar fertilization or drip irrigation for nutrient supplementation is a good approach, and the effect is quick (Liu et al., 2025). The combined use of compost and chemical fertilizers can not only increase the yield, but also improve the soil structure and increase the types of microorganisms (Adhikari et al., 2023).

6.3 Integrated nutrient management (INM): blending organic and synthetic inputs

Integrated nutrient management (INM) advocates the combined use of organic and chemical fertilizers. Many studies have shown that organic fertilizers such as compost, vermicompost and livestock manure, combined with an appropriate amount of chemical fertilizers, can increase cabbage yield by more than 10%, improve nutrition, for example, increase vitamin C and sugar content, and at the same time reduce nitrate and lower environmental harm (Adhikari et al., 2023). If bio-organic fertilizers and microbial agents are added, it will be of greater help to soil health and nutrient absorption by crops (Gao et al., 2023; Bejarano-Herrera et al., 2024).

6.4 Matching fertilizer strategy to cultivar type, soil condition, and climate zone

How to fertilize depends on the variety of cabbage, the fertility of the soil and the local climate. For some high-yield varieties, or the soil itself is fertile, less chemical fertilizer can be applied. Don't let the fertilizer be excessive, otherwise it will be bad for the environment (Cao et al., 2023). Where organic cabbage is grown, some legumes such as peas or broad beans can be rotated. This can provide nitrogen to the soil and is also beneficial for the yield of the next season of cabbage (Yfantopoulos et al., 2024). If it is in arid or semi-arid areas, fertilization should also be combined with watering. For example, watering once every six days and combining it with 100 kilograms of nitrogen fertilizer per hectare can make cabbage grow well (Liang, 2024; Liman et al., 2024).

7 Case Study: Field Comparison of Organic and Conventional Fertilization in Cabbage

7.1 Experimental site, soil type, climatic conditions, and cabbage cultivar

Field trials were mainly conducted in China, Nepal and Europe, covering newly reclaimed plots, loam areas and conventional farmlands. Most of these regions belong to temperate or subtropical zones, where the climate is suitable for the growth of cabbage, and the conditions of rainfall and temperature are relatively ideal. The commonly used cabbage varieties in the experiment include high-yield hybrids such as 'Green Coronet'. Some studies also used Chinese cabbage and non-heading cabbage (Adhikari et al., 2023; Wang et al., 2024).

7.2 Treatment setup and monitoring methodology

Experiments generally adopt a randomized block design and set up different fertilization methods, such as using only organic fertilizers, using only chemical fertilizers, or replacing chemical fertilizers with organic fertilizers by 15%, 30%, 45%, etc. A control group will also be set up, such as no nitrogen fertilizer application or only one type of fertilizer. Some experiments also incorporated technologies such as bio-organic fertilizer, biochar or drip irrigation. The observed contents included plant height, stem diameter, leaf area, yield, quality (such as vitamin C, sugar, nitrate) of cabbage, as well as soil organic matter, total nitrogen, available phosphorus and potassium, enzyme activity and microbial conditions (Saha et al., 2021; Wang et al., 2024).

7.3 Trait performance results: growth, yield, soil response, nutrient balance

Research has found that the use of organic fertilizer or a combination of organic and chemical fertilizers can make cabbages grow better, with higher yields and better quality. Some treatments increased the output by 10% to 35%, vitamin C and sugar by 11% to 19% respectively, and nitrate by 19% to 48% (Wang et al., 2024). Organic fertilizers (such as vermicompost, livestock and poultry manure, humus) can increase the organic matter in the soil, regulate the carbon-nitrogen ratio, enhance enzyme activity and microbial species, and make the soil healthier (Kim et al., 2022; Adhikari et al., 2023). If some chemical fertilizers are reduced and bio-organic fertilizers or biochar are added, the yield will not be reduced and the utilization efficiency of fertilizers can be improved (Zhao et al., 2022). Although long-term sole use of chemical fertilizers can accumulate a large amount of nitrogen, phosphorus and potassium, it will deteriorate the soil structure and is also prone to cause environmental problems (Rempelos et al., 2023; Yfantopoulos et al., 2024).

7.4 Economic and sustainability implications from farmer's perspective

Especially organic fertilizers such as vermicompost and humus can reduce the reliance on chemical fertilizers and pesticides, lower the planting cost, and at the same time improve the quality and market competitiveness of cabbage (Adhikari et al., 2023). Although the yield per unit area is not necessarily higher than that of chemical fertilizers, the overall quality is better, it sells better, and the income is not necessarily lower than that of chemical fertilizers; sometimes it is even higher (Cui et al., 2022). If modern technologies such as drip irrigation and precision fertilization are added, the utilization efficiency of water and fertilizer can be further improved, resulting in better economic benefits (Saha et al., 2021). Moreover, organic fertilizers can also reduce heavy metal and greenhouse gas emissions in the soil, which is more in line with the goals of green agriculture and sustainable development (Sikora et al., 2020; Li et al., 2021).

8 Concluding Remarks

Both organic and chemical fertilizers can have a significant impact on the growth, yield and quality of cabbage. Organic fertilizer can make cabbages grow larger and better, such as increasing fresh weight, the number of leaves, leaf length and transverse diameter. The output of goods can be increased by 10% to 35%, the content of vitamin C, sugar and protein will also rise, and at the same time, the accumulation of nitrates and nitrites can be reduced. Fertilizers are more effective in providing nitrogen, phosphorus and potassium, especially when the previous crop of cabbage is a leguminous crop, which can further enhance soil fertility and yield. The combined use of organic and chemical fertilizers or the application of integrated nutrient management (INM) methods can not only increase yield and head weight, but also improve quality and enhance soil organic matter, which is more beneficial for long-term development. The use of biochar-based fertilizers and controlled-release fertilizers can not only increase yield and nitrogen utilization rate, but also reduce environmental impact.

When growing cabbage, it is recommended to give priority to the combination model of "organic + chemical fertilizer". 75% of the recommended amount of chemical fertilizer can be used, combined with organic materials such as vermicompost, compost or green manure from beans. This can provide more comprehensive nutrients while maintaining sustainable development. When applying nitrogen, do not overdo it. An appropriate amount of nitrogen can not only increase yield and quality but also prevent environmental pollution. Biochar fertilizer, controlled-release fertilizer or microbial agents can also be added. All these can enhance the fertilizer efficiency and make the cabbage more resilient. When fertilizing, it is best to make dynamic adjustments in combination with soil testing and the nutritional status of crops, taking into account the nutrient content of the soil itself, so as to achieve scientific and precise results.

Although there are many research achievements at present, there are still some key issues that need to be further explored. For instance, there is still a lack of long-term positioning tests, making it difficult to assess the long-term effects of different fertilization methods on soil health, microorganisms and yield stability. In addition, research on microbial agents is still not in-depth enough. In the future, it is necessary to study their effects when used in combination with organic and inorganic fertilizers and see if they are applicable in different regions. More importantly, we need to develop precise fertilization technology and establish a system that can make intelligent decisions based on the nutrient requirements of crops, changes in soil nutrients and the characteristics of cabbage. In the future, the fertilization of cabbage should develop in a systematic and sustainable direction, integrating organic fertilizers, chemical fertilizers, microbial agents and new types of fertilizers. Based on the characteristics of the crops, soil conditions and environmental requirements, precise, efficient and environmentally friendly fertilization strategies should be formulated to ensure that yield, quality and ecological benefits are all taken into account.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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