

Case Study

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Analysis on the Application Effect of Soil Testing and Formula Fertilization in Cowpea Planting

Xiaoxi Zhou, Tianxia Guo ✉

Institute of Life Sciences, Jiyang College of Zhejiang A&F University, Zhuji, 311800, Zhejiang, China

✉ Corresponding email: Tianxia.guo@jicaf.orgField Crop, 2025, Vol.8, No.5 doi: [10.5376/fc.2025.08.0023](https://doi.org/10.5376/fc.2025.08.0023)

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Abstract Cowpea (*Vigna unguiculata* L.), as an important economic vegetable crop, is highly sensitive to nutrient supply conditions. Traditional fertilization methods often have problems such as excessive dosage, nutrient imbalance and environmental pollution. This study took the typical cowpea main production area as the research object, and compared and analyzed the effects of two fertilization methods on cowpea yield, root growth, leaf nutrient content, soil organic matter and pH changes. At the same time, the utilization efficiency of nitrogen, phosphorus and potassium fertilizers and the potential impact on the agricultural ecological environment of different fertilization methods were evaluated. The results showed that compared with the traditional fertilization method, soil testing and formula fertilization can significantly improve the yield and quality of cowpea, promote the development of root system and plant robustness, enhance the absorption capacity of nitrogen and other nutrients, and effectively improve soil fertility and structure. This study hopes to promote the green and efficient planting of cowpea and promote the sustainable development of regional agriculture.

Keywords Soil testing and formula fertilization; Cowpea; Yield improvement; Nutrient absorption; Soil improvement

1 Introduction

When planting cowpea (*Vigna unguiculata* L.), the problem of insufficient fertilizer application is often encountered. Especially in some acidic soils such as red soil, phosphorus is easily fixed and nutrients are not easily absorbed by plants. In many cases, traditional fertilization methods are not very effective. They either do not match the needs of crops or the nutrients that the soil can provide. As a result, the yield cannot be increased, and it is easy to cause nutritional imbalance, and more money is spent but there is no effect (Sihotang et al., 2022). Excessive or insufficient use of nitrogen, phosphorus, and potassium will affect the growth of cowpeas, and may also cause poor yield and quality (Sukyankij et al., 2022).

In order to improve this situation, more and more people are now using "soil testing and formula fertilization". This method is quite practical. First, see what is missing in the soil, and then determine how much fertilizer to apply according to the needs of cowpeas, mainly nitrogen, phosphorus, and potassium. Testing methods such as the Olsen method and the Bray-1 method can help determine whether there is enough phosphorus in the soil and then determine how much to apply (Susila et al., 2010). This method is particularly useful in places where soil conditions vary greatly, and can be managed according to the specific conditions of the plots, so that yields can be increased and fertilizers are not wasted.

This study analyzed the effects of soil testing and fertilization on cowpea production, focusing on its effects on soil chemical properties, crop yields and input efficiency, and combined the results of field trials and calibration studies to evaluate the effectiveness of this method in optimizing fertilization, reducing unnecessary inputs and improving farmers' economic benefits. This study hopes to guide the best practices for sustainable cowpea cultivation, promote efficient resource use, and support the wider application of precision agriculture technology in legume production systems.

2 Principles and Application Techniques of Formula Fertilization

2.1 Overview of soil nutrient diagnostic methods

The first step in formulating fertilizer for cowpea is to find out what is missing in the soil. The common practice is to take soil samples first, test the nitrogen (N), phosphorus (P), potassium (K) content, and also measure the pH value and organic matter. After the test, using methods such as the STCR model, you can calculate how much nutrients are needed to achieve a certain yield, and you can also estimate how much soil, fertilizer and organic fertilizer can contribute (Long et al., 2011). Many studies have found that cowpea lacks nitrogen the most, followed by potassium and phosphorus, so special attention should be paid to the amount of nitrogen fertilizer.

2.2 Matching mechanism between supply and demand

Formulated fertilization, to put it simply, is: soil, fertilizer, and farmyard manure, which must match the actual needs of crops at each stage. The usual approach is to first calculate "how much nutrients are needed to produce one ton of cowpea", then deduct the part that can be provided by the soil and organic fertilizer according to the soil inspection results, and then use chemical fertilizers to make up the rest. Now there are many "formula calculators" that can directly input soil inspection data to give specific fertilizer amounts (Pandey et al., 2019). This can not only ensure production, but also reduce waste, be environmentally friendly and save money.

2.3 Intelligent recommendation systems for fertilizer formulations

In recent years, many intelligent fertilizer distribution systems have emerged. They put soil testing, crop fertilizer requirements and local planting habits into a database and automatically calculate the most appropriate fertilizer plan (Beena et al., 2018). Farmers can get accurate suggestions immediately by simply entering the soil inspection results on their mobile phones or computers. Relying on these digital tools, fertilization formulas are more accurate and easier to promote, which can help cowpea cultivation achieve a win-win situation of "high yield, fertilizer saving, and environmental protection".

3 Impacts on Growth Performance of Yard-Long Bean

3.1 Seedling uniformity and early growth

Test the soil first, then match the fertilizer, especially the combination of phosphorus and nitrogen, phosphorus and potassium, so that the cowpea seedlings can grow uniformly and quickly. When the soil lacks phosphorus, add a little phosphorus fertilizer, and the aboveground part of the seedlings will grow more vigorously, which is more obvious for those "fast-responding" varieties (Sukyankij et al., 2022). If you add some organic materials such as earthworm compost, the soil will be looser and have more nutrients, and the vitality of the seedlings can be taken to a higher level (Islam et al., 2016).

3.2 Plant height and leaf area index dynamics

Supplement nitrogen, phosphorus and potassium according to the soil test results, and add a little growth regulator, the plant will grow taller, have more leaves, and have a larger leaf area index. If the nutrition keeps up, the photosynthetic capacity will be strong, and the growth of the whole plant will naturally be good (Sihotang et al., 2022; Nahid et al., 2024).

3.3 Root development and stress resistance

Soil testing and formula fertilization, especially phosphorus supplementation and organic fertilizer, can make the root system thicker and longer. The deeper the roots are, the faster they absorb water and fertilizer, and the more they can withstand drought or nutrient deficiency (Purnama et al., 2025). If root-promoting bacteria (PGPR) and a small amount of lime are added, the root system will be healthier, with fewer diseases and the whole plant will be more vigorous (Yadav et al., 2017). In short, this method can not only make the roots grow longer, but also help cowpeas better resist various stresses.

4 Regulatory Effects on Yield and Quality

4.1 Number of pods and average yield per plant

Test the soil first, then accurately match fertilizers, especially phosphorus, nitrogen, and potassium, and add a little biochar or lime, which can make each plant produce more pods, longer pods, and more and heavier grains

(Adekiya, 2022). If the seeds are inoculated with rhizobia and supplemented with phosphorus at the same time, the yield can be further improved: some experiments have increased the yield from 1 097 kg/hectare to 1 674 kg/hectare (Kyei-Boahen et al., 2017). Using water-soluble fertilizers with drip irrigation and supplementing NPK on demand can also increase the yield of grains and stems.

4.2 Nutritional content and flavor indices

Precise fertilization can also make beans more nutritious. Reasonable combination of NPK and some organic materials can increase the protein, crude protein and trace elements such as iron, manganese and zinc in the grain (Goswami et al., 2022; Iqbal et al., 2024). The test showed that the grain protein can reach 223-252 g/kg, and it is higher after adding formula fertilizer and inoculation. With a good nutrient balance, there will be fewer anti-nutritional factors, and the flavor will naturally be better. However, it should be noted that when the yield is particularly high, the protein content may be "diluted", resulting in a phenomenon of high yield but slightly lower protein.

4.3 Commercial traits and market acceptability

Mix fertilizer according to soil test results to make the pods larger and more uniform, and the market is more willing to buy them. When nitrogen, phosphorus and potassium are used together with organic fertilizers, the pod yield can reach up to 71.6 kg/hectare, and the quality is also better (Gaden et al., 2023). The healthier the soil, the more uniform the product specifications, and it is easier to sell at a good price. In short, applying fertilizers according to the actual needs of the soil and crops can not only stabilize yields and improve quality, but also make more money and reduce waste (Iseki et al., 2023).

5 Soil Nutrient Dynamics and Ecological Feedback

5.1 Trends of available nutrients in soil

Fertilizer allocation based on soil test results can keep nitrogen, phosphorus, and potassium at appropriate levels, with neither deficiency nor excess. Research models show that as long as precise fertilization is followed, combined with practices such as mulching or returning straw to the field, the nutrients in the soil will be more stable and more useful in the long run (Turner and Kodali, 2020). If leguminous crops were planted the previous year, more nitrogen can be retained to help save fertilizer for the next crop (Koyama et al., 2021).

5.2 Changes in soil enzyme activity and microbial community

The amount of fertilizer applied is based on soil conditions, and the enzymes and microbial communities in the soil will also change accordingly. For example, after phosphorus supplementation and lime addition, alkaline phosphatase activity will increase; when no fertilizer is applied, acid phosphatase will become more active (Ndabankulu et al., 2022). In the long run, microorganisms will tend to be those that "eat fast and grow fast"; changes in enzyme activity also indicate that nutrients in the soil are more useful - when there is more nitrogen, the activity of nitrogen-producing enzymes in the soil will be "suppressed" (Nieland et al., 2024). These changes directly determine whether nutrients can be quickly used by plants, and are also related to the overall health of the soil.

5.3 Residual effects and long-term soil fertility

The benefits of fertilizer matching according to soil testing are not only effective in the current season, but also leave nutrient "deposits". The positive feedback brought by legume rotation makes the soil structure better, the nutrient cycle smoother, and the subsequent crops save fertilizer (De Long et al., 2023). After years of persistence, the organic matter in the soil has increased, the microbial diversity has stabilized, and the ecosystem has become more resistant to shocks. In this way, cowpea cultivation can maintain high yields and environmental protection for a long time.

6 Fertilizer Use Efficiency and Environmental Friendliness

6.1. Nutrient use efficiency and leaching control

Applying fertilizer according to the actual soil conditions can significantly improve the efficiency of nutrient use. The soil testing and formula method allows crops to "eat" according to their needs, neither too much nor too little.

In this way, not only can the total amount of fertilizer be reduced, but also the loss of fertilizer washed away by rainwater or seeping into the ground can be reduced (Barlóg et al., 2022). If some enhanced fertilizers or good bacteria (such as root-promoting microorganisms and phosphorus-dissolving microorganisms PSM) are added, the absorption of nitrogen and phosphorus by crops will be better, and the risk of pollution will be lower (Figure 1) (Chen et al., 2018; Bargaz et al., 2018). Some studies have shown that for every 1% increase in the soil testing and formula fertilization rate, 0.09% less chemical fertilizer can be used and 0.04% more yield can be obtained.

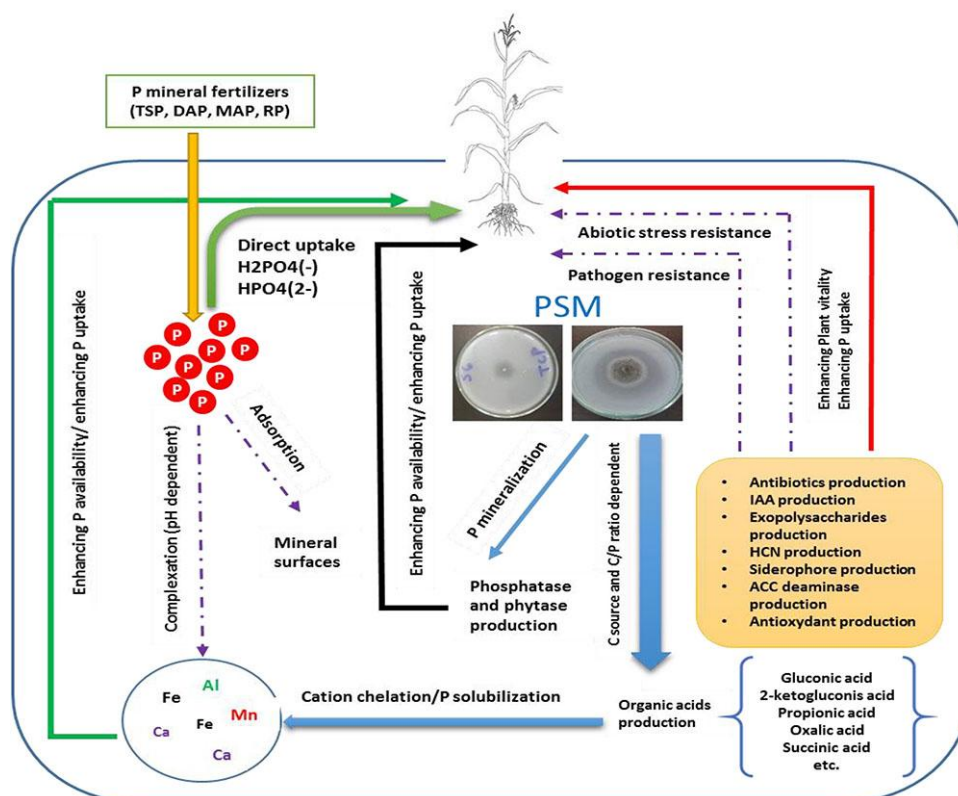


Figure 1 Conceptual overview illustrating the role of P solubilizing microorganisms (PSMs) in enhancing P mineral fertilizers eco-efficiency (Adopted from Bargaz et al., 2018)

6.2. Cost-benefit performance of fertilizer input

Soil testing and formulating can not only increase yield, but also save fertilizer and money. Because fertilization is more accurate and there is no waste, the cost is lower. Once the yield increases, the income will increase. Some studies have found that if farmers in a region use this technology, the overall fertilizer consumption can be greatly reduced, but the yield will not drop, but increase, which is very cost-effective (Luo et al., 2013). Arranging fertilization investment according to soil conditions can also make every penny more worthwhile (Singh et al., 2021).

6.3 Controlling the risk of eutrophication of water bodies

Random fertilization can easily bring excess fertilizer into the water, causing "nutrient excess" in the water body (such as algae growth), which is called eutrophication. Soil testing and formula fertilization can effectively reduce this risk by reducing excess fertilization (Micha et al., 2023; Tian et al., 2023). Some environmentally friendly fertilizers (such as coated fertilizers and slow-release fertilizers) can also slowly release nutrients, blocking rainwater erosion and preventing the fertilizer from running away all at once. These methods are critical to protecting the ecological environment, as they can ensure crop yields while protecting water and soil.

7 Case Studies

7.1 Demonstration and application of modern agricultural park in Deqing County, Zhejiang

In the agricultural park in Deqing, Zhejiang, farmers used soil testing and formula fertilization, and the effect was obvious. Doing soil testing before fertilization and then combining it with organic fertilizers such as biochar can

make the soil more fertile and beans grow better. For example, applying biochar and phosphate fertilizer together can increase the pH value, nitrogen and phosphorus content of the soil, and allow the soil to capture more nutrients. These improvements allow cowpea roots and leaves to grow more nodules and increase beneficial plant components (Table 1) (Phares et al., 2020). These results show that data-guided fertilization methods can help us stabilize production and improve quality in modern agriculture.

Table 1 Rhizosphere soil properties following application of biochar and inorganic phosphorus fertilizer (TSP) (n = 3) (Adopted from Phares et al., 2020)

Treatment	pH	Total N (%)	AvP (mg/kg)	SOC (%)	CEC (cmolc/kg)
Control	5.43 ± 0.03a	0.09 ± 0.02a	7.34 ± 0.09a	0.72 ± 0.00a	4.43 ± 0.10a
BC1.5	5.83 ± 0.03b	0.22 ± 0.04b	11.25 ± 0.43b	1.12 ± 0.03b	5.05 ± 0.07b
BC2.5	6.10 ± 0.01c	0.30 ± 0.02c	13.92 ± 0.67c	1.34 ± 0.02c	6.38 ± 0.05c
BC1.5 + P	5.86 ± 0.01b	0.36 ± 0.03d	23.52 ± 0.79d	1.16 ± 0.04b	5.08 ± 0.10b
BC2.5 + P	6.11 ± 0.01c	0.43 ± 0.03e	26.78 ± 0.65e	1.36 ± 0.02c	6.41 ± 0.04c
% CV	0.4	9.5	3.5	2.3	1.4

Table caption: BC1.5 = biochar at 1.5 t/ha, BC2.5 = biochar at 2.5 t/ha, P = phosphorus fertilizer; CV: coefficient of variation, AvP = available phosphorus, SOC = soil organic carbon, CEC = cation exchange capacity. Each value is presented as mean ± 1 standard deviation. Means in the same column and lettered with same alphabet superscripts are not significantly different at $p < 0.05$ using Fisher's protected LSD test (Adopted from Phares et al., 2020)

7.2 Farmers' self-management plot experiment in Heng County, Guangxi

In Heng County, Guangxi, local farmers also used soil testing and formula methods to grow cowpeas. Through field experiments, they used a method called "crop response model (STCR)" to determine the amount of nitrogen, phosphorus and potassium fertilizers based on the actual soil conditions. This method is also equipped with a calculator and fertilization formula, which is very convenient to use. As a result, farmers not only save fertilizer, but also increase the yield of green beans and use nutrients more evenly. These practices show that even small-scale growers can grow well and make more money as long as they use scientific methods.

7.3 Case study of greenhouse for facility agriculture in Weifang, Shandong

Soil testing and formula fertilization have also been tried in some greenhouses in Weifang, Shandong. Under this facility agriculture condition, farmers first do soil tests, and then use water-soluble fertilizers with irrigation to deliver fertilizers directly to the roots of crops. In this way, the yield of seeds and stems is increased, and the main nutrients in the soil are better absorbed (Jayanthi et al., 2024). Coupled with modern irrigation technology and sophisticated nutrient management, cowpeas can grow fast and well, and keep the soil healthy. This method is particularly suitable for efficient planting in greenhouses.

8 Concluding Remarks

In cowpea cultivation, soil testing and formula fertilization is a very practical technological advancement. The core of this method is to first test the nutritional status of the soil, and then give reasonable fertilization suggestions based on the target yield. Farmers can use chemical fertilizers and organic fertilizers (such as biochar, compost, and green manure) together based on these suggestions, which can not only increase soil fertility but also increase cowpea yield. At the same time, this practice can also improve some important indicators of the soil, such as pH value, organic carbon content, and nutrient utilization rate. Under the premise of ensuring yield, it can reduce the use of chemical fertilizers, which is beneficial to environmental protection and sustainable development.

However, there are also some practical problems in the application process. The soil types, climatic conditions, and farming methods in different regions vary greatly, which may lead to different effects of the same method. In addition, farmers in some areas have difficulty in obtaining soil testing services and do not have a deep understanding of formula fertilization. Some formula suggestions are too general and lack guidance for specific plots. In order to solve these problems, it is necessary to increase the promotion of technology, provide reasonably priced and easy-to-use soil testing services, and promote comprehensive fertilization plans in combination with

local organic resources. At the same time, more demonstration experiments and farmer-participated research should be carried out to improve everyone's acceptance and operational capabilities of scientific fertilization.

In the future, research should focus more on fertilization optimization strategies in different agricultural ecological zones and planting patterns. Some smarter tools can be developed to combine real-time data of soil and crops to help farmers dynamically manage nutrient inputs. In addition, long-term research should be conducted to observe the sustained impact of integrated fertilization on soil health, crop yields and ecological environment. The mechanism of action of some environmentally friendly fertilizers also needs to be explored in depth, including their effects on nutrient flow, nutrient retention and crop quality. Through these efforts, the sustainability of cowpea cultivation will continue to improve, and farmers' income will be more stable and higher.

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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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