Responses of Growth, Quality, Photosynthetic Characteristics, and Nitrogen Utilization of Pak Choi in Guizhou Yellow Soil to Novel Fertilizers (Postprint)

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Date: 2017-11-07T00:00:00+00:00

Abstract

To investigate the effects of different new fertilizers on the yield, quality, photosynthetic characteristics, and fertilizer utilization of Chinese cabbage in acidic yellow soil of Guizhou Province, and to screen suitable new fertilizer products for application in Guizhou yellow soil, a pot experiment was conducted with four treatments: control (CK, no nitrogen fertilizer), conventional compound fertilizer (conventional fertilization), water-retaining functional fertilizer, and stabilized slow-release fertilizer, to study the effects of new fertilizers on Chinese cabbage yield, quality, photosynthetic characteristics, and nutrient uptake and utilization. The results showed that application of water-retaining functional fertilizer and stabilized slow-release fertilizer significantly increased the biomass of Chinese cabbage at 34 days after sowing, with fresh weight increasing by 4.16% and 22.28%, and dry weight increasing by 41.55% and 62.35%, respectively, compared with conventional fertilization. Application of new fertilizers also improved the nutritional quality of Chinese cabbage. Compared with conventional fertilization, water-retaining functional fertilizer significantly reduced nitrate content by 18.61%, while increasing reducing sugar, vitamin C (Vc), and free amino acid contents by 25.74%, 130.95%, and 16.91%, respectively. In contrast, stabilized slow-release fertilizer increased nitrate, reducing sugar, and vitamin C contents by 26.68%, 15.35%, and 50.00%, respectively, but decreased free amino acid content by 14.43% compared with conventional fertilization. Moreover, new fertilizers enhanced the photosynthetic capacity of Chinese cabbage leaves (net photosynthetic rate Pn, stomatal conductance gs, intercellular CO2 concentration Ci, and transpiration rate Tr), with the stabilized slow-release fertilizer treatment showing the best photosynthetic performance, and stomatal factors being the main cause of increased net photosynthetic rate. Application of new fertilizers significantly increased nitrogen uptake and improved nitrogen use efficiency in Chinese cabbage. The average agronomic efficiency of nitrogen fertilizer (AEN), partial factor productivity (PFPN), physiological efficiency (PEN), and apparent recovery efficiency (REN) for new fertilizer treatments were 48.30 kg · kg 1, 59.85 kg · kg 1, 95.46 kg · kg 1, and 52.79%, respectively, with the stabilized slow-release fertilizer treatment showing the best nitrogen use efficiency, particularly an apparent recovery efficiency of 66.66%. Furthermore, correlation analysis results showed that Chinese cabbage yield was significantly positively correlated with leaf net photosynthetic rate Pn, stomatal conductance gs, and transpiration rate Tr, indicating that improving these gas exchange parameters could increase Chinese cabbage yield. Meanwhile, leaf nitrogen content was extremely significantly correlated with physiological efficiency and apparent recovery efficiency of nitrogen fertilizer, with r values of 0.937 and 0.978, respectively, suggesting that increasing leaf nitrogen content could enhance nitrogen use efficiency in Chinese cabbage. In summary, new fertilizers demonstrated significant effects on biomass increase and photosynthetic characteristic improvement of Chinese cabbage in acidic yellow soil of Guizhou Province, providing a reference and theoretical basis for future promotion and application in agricultural production in Guizhou.

Full Text

Response of Chinese Cabbage Growth, Quality, Photosynthetic Characteristics, and Nitrogen Utilization to New Fertilizers in Guizhou Yellow Soil

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This work was supported by the Science and Technology Project of Guizhou Province (2014-7706) and the Independent Innovation Project of Guizhou Academy of Agricultural Sciences (2014-007).
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Received Apr. 29, 2016; accepted Jun. 28, 2016

Abstract

This study investigated the effects of different new fertilizers on the yield, quality, photosynthetic characteristics, and fertilizer utilization of Chinese cabbage grown in acidic yellow soils of Guizhou, aiming to identify suitable fertilizer products for this region. A pot experiment was conducted using typical Guizhou yellow soil (pH 6.08) collected from the experimental base of the Guizhou Academy of Agricultural Sciences. Four treatments were established: a control (CK, no nitrogen fertilizer), conventional compound fertilizer (FH), water-retaining functional fertilizer (BS), and stable slow-release fertilizer (WD). Biomass, nitrate content, reducing sugar, vitamin C (Vc), free amino acid content, leaf gas exchange parameters, nitrogen content, and nitrogen utilization were measured at various times after sowing.

The results demonstrated that at 34 days after sowing, both BS and WD treatments significantly increased Chinese cabbage biomass. Compared with the FH treatment, fresh weights increased by 4.16% and 22.28%, while dry weights increased by 41.55% and 62.35% for BS and WD treatments, respectively. New fertilizer application also improved nutritional quality. The BS treatment significantly reduced nitrate content by 18.61% while increasing reducing sugar, Vc, and free amino acid contents by 25.74%, 130.95%, and 16.91%, respectively, compared with FH treatment. The WD treatment increased nitrate, reducing sugar, and Vc contents by 26.68%, 15.35%, and 50.00%, respectively, but decreased free amino acid content by 14.43% relative to FH treatment. Furthermore, new fertilizers enhanced photosynthetic capacity, as evidenced by increased net photosynthetic rate (Pn), stomatal conductance (gs), intercellular CO_2 concentration (Ci), and transpiration rate (Tr), with WD treatment showing the best performance. Stomatal regulation was identified as the primary factor enhancing photosynthetic capacity.

Nitrogen uptake by Chinese cabbage increased significantly with new fertilizer application, accompanied by marked improvements in nitrogen use efficiency. Average agronomic nitrogen efficiency (AEN), partial factor productivity (PFPN), physiological nitrogen use efficiency (PEN), and recovery efficiency (REN) for new fertilizer treatments were 48.30 $kg \cdot kg^{-1}$, 59.85 $kg \cdot kg^{-1}$, 95.46 $kg \cdot kg^{-1}$, and 52.79%, respectively. The WD treatment exhibited the highest nitrogen use efficiency, particularly for nitrogen recovery efficiency, which reached 66.66%. Correlation analysis revealed significant positive relationships between yield and leaf Pn, gs, and Tr, indicating that improving these gas exchange parameters can increase Chinese cabbage yield. Additionally, leaf nitrogen content showed highly significant correlations with PEN (r = -0.937) and REN (r = 0.978), suggesting that increasing leaf nitrogen content can enhance nitrogen utilization efficiency.

In conclusion, new fertilizers significantly enhanced biological yield and photosynthetic characteristics of Chinese cabbage grown in Guizhou acidic yellow soils, providing a scientific reference and theoretical basis for future applications

of new fertilizers in agricultural production in Guizhou Province.

Keywords: Acid yellow soil; Chinese cabbage; New fertilizer; Biomass; Photosynthetic characteristics; Nitrogen fertilizer use efficiency

1. Materials and Methods

1.1 Experimental Materials

The experiment was conducted in a greenhouse at the Guizhou Institute of Soil and Fertilizer, Guizhou Academy of Agricultural Sciences, from July to September 2015. The test soil was a yellow soil collected from the experimental base of the Academy, with the following basic physicochemical properties: pH 6.08, organic matter 38.37 $g \cdot kg^{-1}$, total nitrogen 1.57 $g \cdot kg^{-1}$, available phosphorus 12.30 $mg \cdot kg^{-1}$, and available potassium 119.00 $mg \cdot kg^{-1}$. Three fertilizer types were used: conventional compound fertilizer (the farmers' customary fertilizer with $N:P_2O_5:K_2O$ = 15:15:15), water-retaining functional fertilizer (containing a water-retaining agent, independently developed by the Guizhou Institute of Soil and Fertilizer, with $N:P_2O_5:K_2O$ = 16:10:16), and stable slow-release fertilizer (containing a urease inhibitor, provided by Guizhou Hualong Fertilizer Co., Ltd., with $N:P_2O_5:K_2O$ = 16:10:16). The test crop was a fast-growing Chinese cabbage variety.

1.2 Experimental Design

Four treatments were established: (1) CK: no nitrogen fertilizer, only phosphorus and potassium; (2) FH: conventional compound fertilizer; (3) BS: water-retaining functional fertilizer; and (4) WD: stable slow-release fertilizer. The test soil was air-dried and passed through a 2 mm sieve. Plastic pots (2 L capacity) were filled with 1.5 kg of soil each. All fertilized treatments received identical amounts of nitrogen, phosphorus, and potassium at rates of 0.15 g N, 0.1 g P_2O_5, and 0.15 g K_2O per kilogram of soil. Deficiencies were supplemented with urea (46% N), calcium superphosphate (12% P_2O_5), and potassium sulfate (50% K_2O), resulting in 0.225 g N, 0.15 g P_2O_5, and 0.225 g K_2O per pot.

Each treatment had nine replicates, totaling 36 pots with one Chinese cabbage plant per pot. Before planting, fertilizers were thoroughly mixed with the soil as basal application. Seeds were sown on the soil surface, watered appropriately, and covered with a thin soil layer to facilitate germination. Soil moisture was maintained consistently across all pots throughout the experiment.

1.3 Sample Collection and Measurement

Plant samples were collected three times during the growth period: 17 days, 34 days, and 50 days after sowing. At each sampling, three representative plants per treatment were selected and transported to the laboratory for analysis.

1.3.1 Soil Basic Physicochemical Properties Before the experiment, the test soil was thoroughly mixed, and a portion was air-dried, ground, and sieved to determine basic physicochemical properties. Soil pH was measured using a pH meter at a soil:water ratio of 2.5:1. Organic matter was determined by the potassium dichromate volumetric method. Total nitrogen was measured by the semi-micro Kjeldahl method with standard acid titration. Available phosphorus was extracted with 0.5 $mol \cdot L^{-1}$ $NaHCO_3$ and determined by the molybdenum-antimony anti-colorimetric method. Available potassium was extracted with 1.0 $mol \cdot L^{-1}$ NH_4OAc and measured by flame photometry.

1.3.2 Plant Sample Measurement After collection, fresh weight was recorded. A portion of fresh samples was killed at 105 °C for 30 minutes, then dried to constant weight at 60 °C. The dried samples were ground and digested with H_2SO_4-H_2O_2 for total nitrogen determination using a Kjeldahl analyzer. Additional fresh samples were used to measure sanitary quality (nitrate content) and nutritional quality (reducing sugar, Vc, and free amino acid content).

1.3.3 Gas Exchange Parameter Measurement During the vigorous growth period on clear days, three uniformly growing Chinese cabbage plants per treatment were selected. Between 9:00 and 11:30 AM, a Li-6400XT portable photosynthesis system (LI-COR, USA) was used to measure net photosynthetic rate (Pn), stomatal conductance (gs), intercellular CO_2 concentration (Ci), and transpiration rate (Tr) of functional leaves. Measurement conditions were set at light intensity of 1,200 $mol \cdot m^{-2} \cdot s^{-1}$, leaf temperature of 25 °C, CO_2 concentration of 400 $mol \cdot mol^{-1}$, and gas flow rate of 300 $mol \cdot s^{-1}$. Stomatal limitation value (Ls) was calculated using the formula:

$$Ls = 1 - \frac{Ci}{Ca}$$

where Ca is the set CO_2 concentration.

1.4 Parameter Calculations

Nitrogen use efficiency parameters were calculated as follows:

- **Agronomic nitrogen efficiency (AEN, $kg \cdot kg^{-1}$)** = (Yield with N - Yield without N) / N application rate
- **Partial factor productivity of nitrogen (PFPN, $kg \cdot kg^{-1}$)** = Yield with N / N application rate
- **Physiological nitrogen use efficiency (PEN, $kg \cdot kg^{-1}$)** = (Yield with N - Yield without N) / (Total N uptake with N - Total N uptake without N)
- **Recovery efficiency of nitrogen (REN, %)** = (Total N uptake with N - Total N uptake without N) / N application rate × 100

1.5 Statistical Analysis

All experimental data were processed using Microsoft Excel 2003. Statistical analysis was performed using SPSS 20.0 and DPS software, and figures were created using Origin 8.0 software.

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2. Results

2.1 Effects of New Fertilizers on Chinese Cabbage Aboveground Biomass

New fertilizers differentially affected Chinese cabbage biomass (Table 1). Fertilization significantly increased biomass. At 17 days after sowing, compared with FH treatment, BS and WD treatments reduced fresh weight by 9.30% and 32.56%, and dry weight by 6.67% and 40.00%, respectively, with WD treatment being significantly lower than both FH and BS treatments. By 34 days after sowing, biomass continued to increase, with BS and WD treatments showing fresh weight increases of 4.16% and 22.28%, and dry weight increases of 41.55% and 62.35% compared with FH treatment, respectively, both significantly higher than FH. At 50 days after sowing, no significant differences in biomass were observed among FH, BS, and WD treatments.

2.2 Effects of New Fertilizers on Chinese Cabbage Quality

Different new fertilizer types improved Chinese cabbage quality to varying degrees (Table 2). FH and BS treatments significantly reduced nitrate content by 18.99% and 34.06% compared with CK, while WD treatment slightly increased nitrate content. FH, BS, and WD treatments significantly increased reducing sugar content by 14.12% to 43.50%, with BS and WD treatments showing increases of 25.74% and 15.35% compared with FH, respectively. Similarly, new fertilizers markedly improved Vc and free amino acid contents. Compared with CK, Vc content increased by 12.00%, 158.67%, and 68.00% under FH, BS, and WD treatments, respectively, with BS and WD treatments increasing by 130.95% and 50.00% compared with FH. Free amino acid content increased significantly by 13.70% and 32.92% under FH and BS treatments compared with CK, but decreased by 2.70% under WD treatment.

2.3 Effects of New Fertilizers on Leaf Gas Exchange Parameters

At 34 days after sowing, nitrogen application significantly affected Pn, gs, and Tr, but had minimal impact on Ci and Ls (Table 3). The CK treatment (no nitrogen) showed significantly lower Pn, gs, and Tr than all nitrogen-fertilized treatments, confirming that nitrogen application enhanced photosynthetic capacity. Compared with FH treatment, BS and WD treatments increased Pn by 27.40% and 117.81%, gs by 29.41% and 58.82%, and Tr by 38.81% and 86.79%, respectively. Ci showed smaller increases of only 2.92% and 3.47%. The WD treatment demonstrated the best photosynthetic performance, followed by BS treatment. Additionally, nitrogen application reduced stomatal limitation values, with WD treatment showing the greatest reduction, though no significant differences were observed among fertilized treatments.

2.4 Effects of New Fertilizers on Nitrogen Content and Accumulation in Chinese Cabbage

Leaf nitrogen content in all treatments decreased progressively during the growth period, averaging 36.63 $g \cdot kg^{-1}$ at 17 days, 14.88 $g \cdot kg^{-1}$ at 34 days, and 10.57 $g \cdot kg^{-1}$ at 50 days after sowing (Figure 1). At 17 days, BS and WD treatments had significantly higher leaf nitrogen content than FH treatment, with an average increase of 16.67 $g \cdot kg^{-1}$. At 34 days, WD treatment showed significantly higher nitrogen content than CK, FH, and BS treatments, exceeding them by 8.90, 7.04, and 4.26 $g \cdot kg^{-1}$, respectively, with significant differences among all nitrogen treatments. At 50 days, WD treatment still maintained significantly higher nitrogen content than other treatments, while differences among other nitrogen treatments were not significant.

New fertilizer types significantly affected nitrogen accumulation (Figure 1). Compared with CK, new fertilizers substantially increased nitrogen accumulation, with increases of 480.6% to 714.7% at 17 days after sowing. BS treatment showed the highest increase, significantly greater than other fertilized treatments, though no significant difference existed between FH and WD treatments. At 34 days, WD treatment exhibited the most significant increase in nitrogen accumulation, averaging 85.04% higher than other nitrogen treatments, with highly significant differences among treatments. At 50 days, WD treatment still showed significantly higher nitrogen accumulation than other nitrogen treatments, while FH and BS treatments did not differ significantly.

[Figure 1: see original paper]

2.5 Effects of New Fertilizers on Nitrogen Use Efficiency in Chinese Cabbage

New fertilizer types differentially affected nitrogen use efficiency (Table 4). Agronomic nitrogen efficiency (AEN), reflecting yield increase per unit nitrogen applied, ranged from 47.41 to 49.78 $kg \cdot kg^{-1}$ across new fertilizer treatments, with no significant differences among them. Partial factor productivity of nitrogen (PFPN), indicating the contribution of nitrogen to yield, was highest under WD treatment at 61.33 $kg \cdot kg^{-1}$, representing an increase of 2.07 to 2.37 $kg \cdot kg^{-1}$ over other fertilized treatments, though differences were not significant. Physiological nitrogen use efficiency (PEN), representing yield increase per unit nitrogen absorbed, was highest under BS treatment at 114.36 $kg \cdot kg^{-1}$, significantly higher than WD treatment, with FH treatment ranking second. For recovery efficiency of nitrogen (REN), WD treatment achieved 66.66%, significantly higher than FH (49.29%) and BS (42.42%) treatments.

2.6 Correlation Analysis Between Biomass, Leaf Nitrogen Content, Gas Exchange Parameters, and Nitrogen Use Efficiency

Correlation analysis revealed that both fresh and dry weights were significantly positively correlated with leaf Pn, gs, and Tr (Table 5). Dry weight also showed significant positive correlation with Ci, while fresh weight did not. Analysis of correlations between leaf nitrogen content and nitrogen use efficiency indicated that nitrogen content was highly significantly negatively correlated with PEN (r = -0.937) and highly significantly positively correlated with REN (r = 0.978), demonstrating that leaf nitrogen content significantly influences nitrogen use efficiency.

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3. Discussion and Conclusion

Compared with conventional fertilizers, new fertilizers benefit crop yield increase and quality improvement. This study found that new fertilizers significantly increased Chinese cabbage biomass at mid-growth stage but had no significant effect on final harvest fresh and dry weights, suggesting that new fertilizers may have greater impact during the growth process rather than on final yield. This aligns with findings from studies on cucumber and pepper, indicating that new fertilizer effects may not be solely reflected in yield, and that time-series observations throughout the crop growth cycle are necessary for more accurate results. Additionally, studies on different soil types have shown that new fertilizers affect soil nutrients differently, particularly during crop growth, which may be an important factor causing differential crop growth responses.

This study also observed that at the early growth stage (17 days after sowing), Chinese cabbage under stable slow-release fertilizer (WD) grew significantly slower than under compound fertilizer (FH) and water-retaining functional fertilizer (BS) treatments. This may be related to the nutrient release characteristics of stable slow-release fertilizer, which releases lower amounts of nutrients during early growth stages but enables efficient nutrient utilization during mid-to-late stages, thus avoiding excessive early release and subsequent nutrient deficiency. Furthermore, different fertilization treatments had varying effects on nutritional quality: compound fertilizer (FH) and water-retaining functional fertilizer (BS) significantly reduced nitrate content, with BS showing the greatest reduction of 34.07%, likely due to the adsorption of NO_3^--N by water-retaining agents. Although stable slow-release fertilizer (WD) slightly increased nitrate content compared with CK, the level remained far below the national safety standard ($3,000 mg \cdot kg^{-1}$), posing no risk of nitrate 超标. Meanwhile, FH, BS, and WD treatments significantly increased reducing sugar content by 13.85% to 43.71%, with BS and WD increasing Vc content by 130.55% and 50.00% compared with FH, respectively, and BS significantly increasing free amino acid content by 16.90% compared with FH. These results demonstrate that new fertilizers significantly improve Chinese cabbage nutritional quality.

Photosynthesis is a crucial factor affecting crop growth, development, and yield formation, with net photosynthetic rate, stomatal conductance, intercellular CO_2 concentration, and transpiration rate serving as important indicators of photosynthetic capacity. This study found that new fertilizers increased Pn, gs, Ci, and Tr in Chinese cabbage leaves, with stable slow-release fertilizer (WD) showing the optimal effect on leaf gas exchange parameters. Photosynthetic rate enhancement can result from stomatal or non-stomatal limitations. Preliminary judgment can be made based on gs changes, but the most reliable criterion is the direction of change in Ci and stomatal limitation value (Ls): increased Ci with decreased Ls indicates stomatal factors, while the opposite indicates non-stomatal factors. The results showed that WD treatment had significantly higher Pn and gs than other treatments, with simultaneous increases in Ci and decreases in Ls, indicating that stomatal factors were the primary cause of increased net photosynthetic rate. This suggests that stable slow-release fertilizer can improve stomatal environment in Chinese cabbage leaves and enhance photosynthetic rate through stomatal regulation.

Currently, nitrogen use efficiency of chemical fertilizers in China is approximately 30% to 35%, and new fertilizers have played a positive role in improving nitrogen use efficiency. Studies have shown that slow-release compound fertilizers increased nitrogen, phosphorus, and potassium use efficiency by 13.9–23.7, 9.6–14.5, and 17.0–22.9 percentage points, respectively, compared with conventional compound fertilizers. Another study found that new urea types increased nitrogen use efficiency by 17.5% for summer maize in fluvo-aquic soil. This study demonstrated that new fertilizers significantly improved nitrogen use efficiency, particularly stable slow-release fertilizer, which achieved AEN, PFPN, PEN, and REN values of 49.78 $kg \cdot kg^{-1}$, 61.33 $kg \cdot kg^{-1}$, 75.02 $kg \cdot kg^{-1}$, and 66.66%, respectively, substantially outperforming conventional compound fertilizer. The reasons may include: (1) urease inhibitors slow nitrogen release from fertilizers, allowing ${NH_4}^+$ and ${NO_3}^-$ to remain in soil for extended periods and increasing crop nitrogen absorption and utilization; and (2) urease inhibitors effectively reduce soil urease activity and ammonia volatilization losses, thereby improving nitrogen use efficiency.

In summary, new fertilizers showed significant effects on Chinese cabbage biological yield increase and photosynthetic characteristic enhancement in Guizhou yellow soil. However, this study was conducted under pot experiment conditions, and external factors may cause variations in fertilizer effectiveness. Therefore, future research will combine field experiments to further validate these effects, aiming to provide solid and reliable theoretical support for the promotion and application of new fertilizers in Guizhou vegetable production.

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Note: Figure translations are in progress. See original paper for figures.