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Effects of Combined Biochar and Organic Amendment Application on Soil Fertility and Maize Growth: Postprint

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Abstract

Biochar has been widely applied as a multifunctional soil amendment material; however, comparative studies with traditional organic materials and their combined application remain limited. Through pot experiments, we investigated the effects of biochar, straw, and fermented chicken manure applied individually and in combination on nutrient content, enzyme activity, and maize growth in loamy fluvo-aquic soil and sandy soil, and employed principal component analysis to comprehensively evaluate the soil amendment effects of the three organic materials. The experiment consisted of six treatments: no organic material addition (CK), biochar addition (BC), wheat straw (WS), fermented chicken manure (CM), straw and biochar (WS+BC), and chicken manure and biochar (CM+BC). Results indicated that all treatments increased maize biomass and plant height in sandy soil, with the enhancement magnitude of the three organic materials following the order: chicken manure > biochar > straw; chicken manure also increased maize biomass and plant height in loamy fluvo-aquic soil. Addition of biochar and organic materials also increased soil organic matter content, with biochar showing the greatest enhancement. Furthermore, the three organic materials exhibited differential effects on soil nutrients and enzyme activities. Individual application of chicken manure increased alkaline hydrolyzable nitrogen by 22.08% and 26.67%, available phosphorus by 91.92% and 53.65%, and urease activity by 40.54% and 36.94% in loamy fluvo-aquic soil and sandy soil, respectively. Individual application of biochar increased available phosphorus by 83.52% and 89.91%, available potassium by 79.38% and 127.02%, and catalase activity by 3.41% and 11.22% in loamy fluvo-aquic soil and sandy soil, respectively, but decreased soil alkaline hydrolyzable nitrogen content, and when combined with chicken manure, it inhibited nitrogen availability from the manure. Individual application of straw increased available potassium by 49.48%

and 63.02%, and β-glucosidase activity by 51.86% and 59.09% in loamy fluvo-aquic soil and sandy soil, respectively. Combined application of biochar with chicken manure or straw could more balancedly improve soil fertility. Through principal component analysis and correlation analysis, maize biomass and plant height showed extremely significant positive correlations with the scores of the second principal component (PC2), which represented positive changes in soil nitrogen and phosphorus supply. Therefore, among the three organic materials, chicken manure exerted the greatest influence on soil nitrogen and phosphorus contents and related enzyme activities; straw had a greater impact on soil potassium and cellulose decomposition-related enzymes; while biochar provided more balanced improvement in soil fertility and achieved the highest comprehensive soil fertility score. Combined application of straw or chicken manure with biochar could more comprehensively enhance soil fertility.

Full Text

Introduction

Soil fertility and productivity are fundamental to ensuring food security. Globally, limited potential for arable land expansion represents a major constraint on food production, making intensive agriculture and increased per-unit grain output the only viable path to meet growing food demands. Fertilization serves as the primary means of maintaining soil fertility and constitutes an extremely important factor driving grain yield growth. While the chemical fertilizer industry has developed rapidly in recent years and plays a pivotal role in grain production as a basic element ensuring high yields, the proportion of organic fertilizers has steadily declined. Excessive chemical fertilizer application has not only diminished its annual contribution to yield increases but also caused soil quality degradation. Active organic carbon in farmland soils is being depleted year by year, leading to reduced cation exchange capacity, accelerated mineral nutrient leaching, and decreased fertilizer use efficiency. Therefore, emphasizing organic fertilizer application, improving the utilization efficiency of agricultural waste, and promoting integrated organic-inorganic fertilization technology represent inevitable trends for enhancing soil fertility and grain production capacity. The beneficial effects of organic fertilizers on soil fertility have been extensively documented, demonstrating improvements in soil aggregate structure and stability, reduced bulk density, enhanced physicochemical properties, and increased microbial activity and enzyme activity.

Biochar, produced through pyrolysis of crop straw under complete or partial anoxic conditions, has gradually attracted attention for agricultural applications. With its unique porous structure and abundant mineral nutrients, biochar can improve soil water and nutrient retention capacity and aeration, increase microbial activity, and enhance crop yields, making it a novel soil amendment material. Biochar can also serve as a fertilizer synergist, reducing nutrient leaching from chemical fertilizers, increasing nitrogen use efficiency, maintaining soil organic matter stability, slowing decomposition of active organic carbon in organic fertilizers, and reducing carbon emissions. Consequently, combined application of biochar with organic or chemical fertilizers has become a research hotspot in recent years, offering new directions for efficient fertilizer utilization.

Previous studies have found that combined biochar and organic fertilizer application can overcome individual limitations, more comprehensively enhance soil carbon pool reserves and nutrient content, further improve crop nutrient uptake efficiency, and increase crop yields. However, the soil improvement effects of combined organic fertilizer and biochar application may be constrained by numerous factors, such as organic fertilizer type, biochar feedstock and production technology, and soil type. Therefore, this study selected fluvo-aquic loamy soil from Henan Province' s major grain-producing areas and sandy soil developed from Yellow River flood deposits as research subjects to investigate the effects of wheat straw biochar, fermented chicken manure, and wheat straw on soil nutrient status, enzyme activity, and maize growth, providing a theoretical basis for field application of biochar and organic fertilizers.

1 Materials and Methods

1.1 Experimental Materials

The test soils were collected from 0–20 cm tillage layers in Xinxiang City, Henan Province, within a wheat-maize double-cropping rotation system, comprising fluvo-aquic loamy soil and sandy soil developed from Yellow River flood deposits. The loamy soil had pH 8.01, organic matter 12.6 $g \cdot kg^{-1}$, total nitrogen 0.92 $g \cdot kg^{-1}$, available nitrogen 75.5 $mg \cdot kg^{-1}$, available phosphorus 24.8 $mg \cdot kg^{-1}$, and available potassium 192.3 $mg \cdot kg^{-1}$. The sandy soil had pH 8.25, organic matter 8.3 $g \cdot kg^{-1}$, total nitrogen 0.78 $g \cdot kg^{-1}$, available nitrogen 63.0 $mg \cdot kg^{-1}$, available phosphorus 39.5 $mg \cdot kg^{-1}$, and available potassium 146.2 $mg \cdot kg^{-1}$.

The test maize variety was 'Huayu-12' . Organic materials included biochar (BC), wheat straw (WS), and fermented chicken manure (CM). Wheat straw was collected in May 2015 before wheat harvest, then dried and crushed in the laboratory. Fermented chicken manure was a commercial product made from fresh chicken manure with added microbial strains, high-temperature fermentation, baking, and screening. Biochar was self-made straw charcoal: wheat straw was dried, crushed, packed into ceramic crucibles with lids, heated to 350 ℃ under oxygen-limited conditions, held for 4 h, then naturally cooled to room temperature and bagged for use. Nutrient contents of the organic materials are shown in Table 1 .

1.2 Experimental Design

A pot experiment was conducted with six treatments: control (CK), biochar addition (BC), wheat straw addition (WS), fermented chicken manure addition (CM), wheat straw plus biochar (WS+BC), and chicken manure plus biochar

(CM+BC). Each treatment had three replicates. Application rates for biochar, wheat straw, and fermented chicken manure were all 1.5% of air-dried soil mass. The experiment used 20 cm × 10 cm (diameter × depth) plastic pots, each containing 2.5 kg of air-dried, sieved (2 mm) soil.

Before sowing, urea, ammonium dihydrogen phosphate, and potassium chloride were applied at rates of N 0.20 g, P_2O_5 0.15 g, and K_2O 0.20 g per kg soil. All inorganic fertilizers and organic materials were applied as base fertilizer in a single application. The experiment was established on May 20, 2015, with maize seeds sown (10 seeds per pot). After emergence, three uniformly growing plants were retained per pot. All treatments received consistent daily management. On July 20, 2015, maize plant growth was investigated and samples were collected.

1.3 Sample Collection and Analysis

Plant sample collection: All three plants from each pot were removed, washed sequentially with tap water and deionized water, dried with absorbent paper, cut at the uppermost nodal root, separated into shoots and roots, and measured for plant height and root length. Shoots and roots were then mixed and placed in kraft bags, oven-dried, and weighed to determine dry biomass.

Soil sample collection: After plant sampling, soil in each pot was thoroughly mixed, and approximately 500 g was obtained by quartering. Soil samples were air-dried in shade, sieved through 1 mm and 0.15 mm screens, and bagged for use.

Soil nutrient content and enzyme activity determination: Soil pH was measured using a pH meter at a soil:water ratio of 2.5:1. Soil organic matter was determined by potassium dichromate volumetric method, total nitrogen by sulfuric acid accelerator digestion-Kjeldahl method, available nitrogen by alkaline diffusion method, available phosphorus by 0.5 $mol \cdot L^{-1}$ $NaHCO_3$ extraction-molybdenum blue colorimetry, and available potassium by ammonium acetate extraction-flame photometry. Soil urease activity was measured by phenol-sodium hypochlorite colorimetry, catalase activity by potassium permanganate titration, sucrase and cellulase activities by 3,5-dinitrosalicylic acid colorimetry, and L-asparaginase and β-glucosidase activities by methods described by Wu et al.

1.4 Data Analysis

All data were statistically analyzed using Microsoft Excel 2003 and SPSS PASW Statistics 18.0, with figures prepared using SigmaPlot 10.0.

2 Results and Analysis

2.1 Effects of Biochar and Organic Materials on Maize Biomass and Growth

As shown in Table 2 , addition of biochar and organic materials had no significant effect on maize root length in either soil type but promoted plant height and biomass to varying degrees. In loamy fluvo-aquic soil, biochar and straw addition had no significant effect on maize biomass or plant height, whereas chicken manure treatments (CM and CM+BC) significantly increased both parameters. Compared with the control, biomass increased by 62.36% and 72.70%, and plant height increased by 21.09% and 22.46%, respectively. In sandy soil, all treatments significantly increased maize biomass and plant height, with biochar and chicken manure showing superior effects to straw. Biomass in BC, WS, CM, WS+BC, and CM+BC treatments increased by 57.15%, 29.55%, 58.70%, 51.75%, and 69.33% compared with the control, while plant height increased by 28.43%, 21.93%, 45.75%, 29.72%, and 42.05%, respectively. Overall, the three organic materials ranked as chicken manure > biochar > straw in their effects on maize biomass and plant height, with chicken manure plus biochar showing the best synergistic effect.

2.2 Effects of Biochar and Organic Materials on Soil Nutrients

The test soils were alkaline, with pH values of 8.01 and 8.25 for loamy and sandy soils, respectively. Addition of alkaline biochar did not significantly affect pH in either soil, whereas WS+BC significantly increased pH in both soils, and CM and CM+BC significantly decreased pH in sandy soil.

In loamy soil, single applications of straw and chicken manure did not significantly increase soil organic matter, whereas the three biochar-containing treatments (BC, WS+BC, CM+BC) significantly increased organic matter content by 63.15%, 84.84%, and 83.72%, respectively. Sandy soil had lower organic matter content than loamy soil, and all treatments showed more pronounced enhancement effects, with BC, WS, CM, WS+BC, and CM+BC significantly increasing organic matter by 115.62%, 37.88%, 51.93%, 177.57%, and 114.09%, respectively. Single applications of the three organic materials did not significantly affect total nitrogen content, whereas WS+BC and CM+BC significantly increased total nitrogen in loamy soil, and CM+BC significantly increased total nitrogen in sandy soil (Table 3). Overall, organic material addition showed more pronounced effects on organic matter improvement in sandy soil with weaker buffering capacity, with biochar demonstrating the best enhancement effect.

The three organic materials showed differential effects on soil available nitrogen. Biochar exhibited a decreasing effect on soil available nitrogen, reaching significance in sandy soil. Straw had no significant effect, while chicken manure significantly increased available nitrogen content by 22.08% and 26.67% in loamy and sandy soils, respectively. However, combined application with biochar (CM+BC) showed no significant effect on available nitrogen in either soil.

For soil available phosphorus, biochar and chicken manure showed significant promoting effects in loamy soil, while single straw application had no significant effect. BC, CM, WS+BC, and CM+BC treatments increased available phosphorus by 83.52%, 91.92%, 80.33%, and 171.26% compared with the control. In sandy soil, all three organic materials significantly increased available phosphorus, with biochar and chicken manure showing superior effects to straw. BC, WS, CM, WS+BC, and CM+BC treatments increased available phosphorus by 89.91%, 36.69%, 53.65%, 92.88%, and 116.19%, respectively.

Biochar and straw, rich in free potassium, significantly increased soil available potassium content. In loamy soil, BC, WS, WS+BC, and CM+BC treatments increased available potassium by 79.38%, 49.48%, 129.89%, and 90.72%, respectively. In sandy soil, the increases were 127.02%, 63.02%, 146.02%, and 130.00%, respectively (Table 3).

Overall, the three organic materials showed distinct effects on soil available nutrients. Biochar substantially increased available phosphorus and potassium but inhibited nitrogen availability from both soil and organic materials. Chicken manure effectively increased available nitrogen and phosphorus, while straw enhanced available potassium. Combined application of biochar with chicken manure or straw compensated for individual limitations and more comprehensively improved soil nutrient content.

2.3 Effects of Biochar and Organic Materials on Soil Enzyme Activities

Soil enzyme activity serves as an important biological indicator of soil quality. As shown in Table 4 , BC, WS, and WS+BC had no significant effect on urease activity in sandy soil but decreased urease activity in loamy soil, whereas CM and CM+BC significantly increased urease activity in both soils. Treatments showed varied effects on L-asparaginase activity: WS, WS+BC, and CM+BC significantly increased L-asparaginase activity in loamy soil, while all treatments significantly increased L-asparaginase activity in sandy soil, with straw alone showing the highest activity.

No treatments significantly affected sucrase activity in either soil type, though WS treatment showed significantly higher sucrase activity than BC, CM, and CM+BC in sandy soil.

Catalase, an oxidoreductase involved in soil material and energy transformation, showed higher activity in loamy than sandy soil, with sandy soil catalase activity being more sensitive to exogenous organic material input. In loamy soil, BC, WS+BC, and CM+BC significantly increased catalase activity, while WS and CM had no significant effect. In sandy soil, all treatments increased catalase activity, with biochar-containing treatments (BC, WS+BC, CM+BC) showing significantly higher activity than WS and CM treatments.

Cellulase, a complex enzyme system degrading soil cellulose to glucose, showed no significant response to straw addition despite straw' s high cellulose content. Only WS+BC significantly increased cellulase activity in sandy soil. β-glucosidase, an important component and limiting factor of soil cellulase, was substantially increased by straw treatments (WS and WS+BC) in both soils, while other treatments had no significant effect (Table 4).

2.4 Comprehensive Evaluation of Soil Fertility Under Different Fertilization Conditions Using Principal Component Analysis

In loamy soil, principal component analysis (PCA) of soil nutrient contents and enzyme activities under different organic material applications identified two principal components with eigenvalues >1. The first (PC1) and second (PC2) principal components explained 47.39% and 27.78% of variance, respectively, with a cumulative contribution of 75.16%, representing the main factors influencing soil fertility. Principal components are linear combinations of indicators. Based on eigenvectors for each indicator in the principal components, the relationships for PC1 and PC2 expressed by standardized variables were:

$$PC1 = 0.3439X_1 + 0.3205X_2 - 0.2427X_3 + 0.1058X_4 + 0.4088X_5 - 0.2587X_6 - 0.1738X_7 + 0.3637X_8 + 0.3332X_9 + 0.2681X_{10} + 0.2553X_{11}$$

$$PC2 = 0.3129X_1 + 0.1723X_2 + 0.3402X_3 + 0.5243X_4 + 0.1678X_5 + 0.4380X_6 + 0.2816X_7 - 0.1119X_8 + 0.2148X_9 - 0.2618X_{10} - 0.2595X_{11}$$

Where X_1 represents organic matter, X_2 total nitrogen, X_3 available nitrogen, X_4 available phosphorus, X_5 available potassium, X_6 urease, X_7 sucrase, X_8 catalase, X_9 L-asparaginase, X_{10} cellulase, and X_{11} β-glucosidase. Coefficients represent the weight of each factor in PC1 and PC2, with positive signs indicating positive correlation and negative signs indicating negative correlation. Underlined values indicate major loading factors with greater absolute values contributing more to the principal component.

As shown in Figure 1a [Figure 1: see original paper], PC1 and PC2 reflected different soil fertility indicator changes. PC1 primarily reflected changes in organic matter, total nitrogen, available potassium, catalase, L-asparaginase, cellulase, and β-glucosidase (all positively correlated). PC2 mainly reflected changes in organic matter, available nitrogen, available phosphorus, urease, sucrase, and β-glucosidase, with β-glucosidase negatively correlated and others positively correlated.

PC1 and PC2 scores for each treatment were calculated from the principal component equations, and comprehensive scores were further calculated through a comprehensive principal component function model. Treatment rankings were: WS+BC > CM+BC > BC > WS > CM > CK (Figure 2 [Figure 2: see original paper]). Additionally, PC1 and PC2 scores revealed different emphases of organic materials on soil fertility: straw increased PC1-related indicators, chicken manure significantly increased PC2-related indicators, while biochar improved both PC1 and PC2 indicators, with greater PC1 enhancement than straw but less PC2 enhancement than chicken manure (Figure 1b).

In sandy soil, PCA identified three principal components with eigenvalues >1. PC1, PC2, and PC3 explained 46.38%, 21.45%, and 13.64% of variance, respectively, with a cumulative contribution of 81.47%. The relationships expressed by standardized variables were:

$PC1 = 0.4125X_1 + 0.2001X_2 - 0.1285X_3 + 0.3682X_4 + 0.4301X_5 - 0.0928X_6 - 0.4146X_7 + 0.4078X_8 + 0.2221X_9 + 0.2073X_{10} + 0.1785X_{11}$

$PC2 = 0.0712X_1 + 0.2538X_2 + 0.5047X_3 + 0.3295X_4 + 0.0603X_5 + 0.5217X_6 - 0.0733X_7 + 0.1078X_8 - 0.0263X_9 - 0.1918X_{10} - 0.5274X_{11}$

$PC3 = 0.0224X_1 - 0.4133X_2 + 0.3973X_3 - 0.0177X_4 - 0.1016X_5 + 0.4217X_6 + 0.0681X_7 - 0.0515X_8 + 0.3353X_9 + 0.3310X_{10} + 0.4441X_{11}$

As shown in Figure 3a [Figure 3: see original paper], PC1, PC2, and PC3 reflected different soil fertility indicator changes. PC1 primarily reflected changes in organic matter, available phosphorus, available potassium, sucrase, and catalase (all positively correlated). PC2 mainly reflected changes in available nitrogen, available phosphorus, urease, cellulase, and β-glucosidase, with cellulase and β-glucosidase negatively correlated and other indicators positively correlated. PC3 primarily reflected changes in total nitrogen, available nitrogen, urease, L-asparaginase, cellulase, and β-glucosidase, with total nitrogen negatively correlated and other indicators positively correlated.

The comprehensive score ranking in sandy soil was consistent with loamy soil: WS+BC > CM+BC > BC > WS > CM > CK (Figure 2). Different treatments emphasized different soil fertility aspects: straw increased PC1- and PC3-related indicators, chicken manure increased PC2- and PC3-related indicators, while biochar increased PC1- and PC2-related indicators, with greater PC1 enhancement than straw but less PC2 enhancement than chicken manure (Figure 3b).

Correlation analysis revealed that in both loamy and sandy soils, maize biomass and plant height were highly significantly positively correlated with PC2 scores, which represented positive changes in soil nitrogen and phosphorus supply. This indicates that soil nitrogen and phosphorus supply capacity was the main factor limiting maize seedling growth and biomass accumulation (Figure 4 [Figure 4: see original paper]).

3 Discussion and Conclusion

Organic fertilizer is an important soil amendment material that can release mineral nutrients for plant uptake while increasing soil organic matter, improving soil physical properties, and promoting microbial activity and enzyme activity. Organic fertilizers have diverse sources and varieties, with type and properties being the main determinants of their amelioration effects. This study found that biochar significantly increased soil organic matter, available phosphorus, and available potassium content but showed a decreasing trend in soil available nitrogen and inhibited nitrogen availability from chicken manure. Biochar is a carbon-rich material containing abundant phosphorus and potassium that can directly increase soil carbon storage and available phosphorus and potassium. However, nitrogen volatilization during pyrolysis makes its contribution to soil nitrogen very limited, and its porous structure and oxygen-containing functional groups can adsorb and fix NH_4^+ from soil and fertilizers, temporarily reducing soil nitrogen availability. Fermented chicken manure contains abundant organic nitrogen and phosphorus that decomposes rapidly, enhancing soil nitrogen and phosphorus supply capacity. Xie et al. also found that chicken manure application significantly increased soil organic matter, available nitrogen, and available phosphorus, consistent with our results. Potassium in crop straw exists mainly in ionic form, representing an important resource of readily available potassium that can increase soil available potassium, a conclusion also supported by this study. Overall, the three organic materials showed differential effects on soil available nutrients: biochar increased available phosphorus and potassium but inhibited nitrogen availability from soil and organic materials; chicken manure effectively increased available nitrogen and phosphorus; and straw enhanced available potassium.

Soil enzyme activity is an important biological indicator that plays a crucial role in soil nutrient cycling and responds more sensitively to soil quality changes than physical and chemical properties. This study showed that all treatments increased soil enzyme activity, though effects varied among different enzymes, consistent with related research findings. Chicken manure significantly increased urease activity in both soils, while biochar and straw had no significant effect and even decreased urease activity in loamy soil. This may be because chicken manure contains richer organic nitrogen with lower C/N ratio, facilitating mineralization after application and stimulating urease activity, whereas biochar and straw with higher C/N ratios suppressed urease activity in loamy soil. Soil oxidoreductases are important enzymes whose response to exogenous biochar remains controversial. Yang et al. and Masto et al. found that biochar substantially increased catalase activity, consistent with our results, though reports of biochar suppressing catalase activity also exist. Differences in test soil types and biochar production conditions and application rates may be the main reasons for these contradictory results. Soil cellulase is a complex enzyme system degrading cellulose to glucose, while β-glucosidase is an important component and limiting factor. Although straw contains abundant cellulose, its addition did not significantly affect cellulase activity in either soil but substantially increased β-glucosidase activity. Therefore, under our experimental conditions, β-glucosidase may be the main factor limiting cellulose decomposition from straw.

Soil physical, chemical, and biological properties all affect crop growth and biomass accumulation. Principal component analysis can comprehensively evaluate soil fertility quality and identify main fertility factors limiting crop growth under different treatments. PCA revealed consistent treatment rankings in both soils: WS+BC > CM+BC > BC > WS > CM > CK, though different organic materials contributed differently to principal component scores. In loamy soil, soil fertility factors were divided into two principal components: biochar- and straw-amended soils had higher PC1 scores, while chicken manure-amended soil had the highest PC2 score, followed by biochar, with straw having no effect. Correlation analysis showed no significant relationship between maize biomass/plant height and comprehensive soil fertility scores, but highly significant positive correlation with PC2 scores. PC2 primarily reflected positive changes in organic matter, available nitrogen, available phosphorus, urease, and sucrase. Since sucrase activity was not significantly affected by any treatment, the main factors promoting maize growth after organic material addition were improved soil organic matter and nitrogen/phosphorus supply capacity, with similar conclusions in sandy soil. This may be because the experimental period was short, focusing on seedling-stage maize biomass and plant height, with nitrogen and phosphorus having more significant effects on vegetative growth at this stage. Qi et al. also found that nitrogen deficiency had the greatest impact on maize seedling growth, followed by phosphorus deficiency, while potassium deficiency had minimal effect. The effects of these three organic materials on maize vegetative growth and grain yield under field conditions require further research.

In summary, biochar, fermented chicken manure, and straw all improved soil nutrient content and enzyme activity but showed different emphases. Biochar increased available phosphorus and potassium and catalase activity but inhibited nitrogen availability from soil and organic materials. Chicken manure effectively increased available nitrogen, available phosphorus, and urease activity, while straw enhanced available potassium and β-glucosidase activity. Under our experimental conditions, soil nitrogen and phosphorus supply capacity was the main factor affecting maize seedling growth, with chicken manure showing the best promotion effect, followed by biochar, while wheat straw had no significant effect. The combination of principal component analysis and correlation analysis can accurately reflect soil fertility levels and predict soil productivity, providing intuitive comparison of soil fertility responses to exogenous organic material input. Overall, straw and chicken manure showed different soil amelioration effects, while biochar provided more balanced soil fertility improvement with the highest comprehensive soil fertility score. Combined application of biochar with appropriate organic materials based on soil nutrient limitations represents a more comprehensive soil improvement measure.

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