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Effects of Poultry Manure and Biochar on Acrisol Soil Properties and Yield of Common Bean. A Short-Term Field Experiment

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Abstract: Common bean is usually cropped under rainfed conditions and in soils with low pH and water retention, in the sub-humid and semiarid regions of Brazil. To improve soil conditions, smallholder farmers commonly use cattle manure. However, manure is available in limited amounts, insufficient to fertilize all cropping areas. Thus, other amendments, such as poultry manure (PM) and biochar (BC), have been proposed to increase soil water retention and pH. We evaluated the effects of BC (10, 20, and 40 t ha^{-1}; BC10, BC20, and BC40, respectively), PM (5 t ha^{-1}; PM), the combination of both amendments (BC10 + PM, BC20 + PM, and BC40 + PM) and an absolute control (Control), with no amendment, on soil physical, chemical, and biological properties, and on common bean water use efficiency (WUE) and yield. The treatments had no effects on total organic carbon, cation exchange capacity, microbial biomass carbon, soil physical properties, and evapotranspiration. Treatment combination BC (10 t ha^{-1}) + PM (5 t ha^{-1}) significantly improved phosphorus concentration, enzymatic activities, WUE, and bean yield in this one-year experiment and it can be a viable management practice for smallholder farmers in the Brazilian sub-humid region. However, further investigations are required to study the long-term field effects of the best performing soil amendments.

Keywords: biochar; poultry manure; evapotranspiration; sustainable agriculture; soil health

1. Introduction

Population growth is increasing the demand for agricultural products [1,2], which can increase land degradation due to intensive agricultural use, often of marginal areas. Land degradation impacts many soil physical, chemical, and biological properties, including organic carbon [3,4], hydraulic conductivity [5,6], bulk density, runoff and erosion [6,7], nutrient availability, microbial biomass, and enzyme activities [8,9]. Land degradation is a worldwide problem, particularly in sub-humid, semiarid, and arid regions [1,10]. In these regions, water shortage, due to rainfall scarcity and irregular temporal and spatial distribution, exacerbates the difficulty in maintaining and/or increasing agricultural yield.

In the sub-humid and semiarid regions of Brazil, besides water problems, there are large areas with low fertility and low water retention capacity soils [11,12]. Cattle manure is commonly added to increase total organic carbon content (TOC) and nutrient availability, to reduce acidity, and to raise the water retention capacity. However, cattle manure availability is insufficient to fertilize all cropping areas and it usually has low mineral nutrient concentrations, due to the system of extensive cattle raising [13].

The intensification of poultry production is providing another manure source [14,15], but this manure is not traditionally used in the region [13]. As other manures, the concentration of nutrients is relatively low, implying high costs of transportation and distribution, and the added organic matter is usually mineralized within only a few cropping seasons. Therefore, applications have to be frequently repeated to maintain soil productivity [16].

An alternative or complementary organic amendment is biochar (BC) [1,16–20]. BC is the result of the pyrolysis process of different biomass types, and it is rich in carbon [21], although lower in nutrients than manures [22,23]. Positive effects of BC application on soil physical, chemical, and biological properties and crop yield have been reported in many studies [18,24–27], although other studies show none or unfavorable consequences on soil properties and crop yield [28–31]. The amelioration of soil properties, such as decreased soil acidity and increased of nutrient concentrations and soil water retention, can be responsible for increased crop yields in soils amended with biochar [18,20,24–26].

The scarcity of scientific reports in the study area that combined BC and poultry manure (PM) and simultaneously evaluated soil physical, chemical, and biological properties plus crop yields led to the establishment of the present work. To our knowledge, this is the first work to combine all these evaluation in a field experiment of a common bean crop under rainfed conditions in a tropical sub-humid climate. We hypothesized that the combination of BC and PM improves bean yield and soil properties in relation to the amendment with the isolated organic amendments.

2. Materials and Methods

2.1. Study Site and Treatments

One field experiment was conducted at the Research Farm, Federal Rural University of Pernambuco, Garanhuns municipality (08°48′34.2″ S, 36°24′29.3″ W), Pernambuco state, Brazil, during the cropping season of 2019. The experiment was intended to be conducted for two more years, but the planting in 2020 was not made due to the Covid pandemic. According to Köppen's classification system, the climate of the area is As' [32], with annual rainfall averaging 918 mm, concentrated between April and August [33]. The predominant soil is Acrisol [34]. The soil texture of the studied site was determined according to Donagemma et al. [35], and is shown in Table 1.

Table 1. Soil texture of topsoil in the experimental area.

Characteristic	Granulometric Fractions
Sand (g kg^{-1})	586
Silt (g kg^{-1})	94
Clay (g kg^{-1})	320
Textural class	Sandy clay loam

The experiment had eight treatments, arranged in a completely randomized block design, with three replicates, totalizing 24 plots. Each plot was 3 m × 4 m (12 m^2). Blocks were 2 m apart and plots were 1 m apart. The treatments were BC, applied in doses equivalent to 10 (BC10), 20 (BC20), and 40 (BC40) t ha^{-1}; PM at 5 t ha^{-1}; this same dose of PM combined with BC, also in doses of 10 (BC10 + PM), 20 (BC20 + PM), and 40 (BC40 + PM) t ha^{-1}, and an absolute control (Control), with no amendment. These doses are in the range commonly applied in Brazil and other countries [14,18,22,23,26].

The BC was obtained by oxygen free pyrolysis in traditional charcoal producing kilns, fed with hardwood, such as *Anacardium occidentale* L. and *Byrsonima crassifolia* (L.). The temperature inside the kiln, monitored with a thermocouple, averaged 500–550 °C for 24–48 h. The BC was ground, sieved to 2 mm, and analyzed (Table 2) for pH, TOC, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) concentrations, using the methodology recommended by Donagemma et al. [35]. The PM was obtained from local poultry producers and analyzed for pH, TOC, and nitrogen (N), P, K, Ca, and Mg concentrations (Table 2), using the methodology recommended by Donagemma et al. [35].

Table 2. Selected chemical characteristics of the biochar and poultry manure used in the experiment.

Characteristic	Biochar	Characteristic	Poultry Manure
pH	9.8	pH	8.9
Total organic carbon, g kg^{-1}	543	Total organic carbon, %	23.7
Phosphorus, mg kg^{-1}	2.0	Phosphorus, %	4.8
Potassium, $cmol_c$ kg^{-1}	3.9	Potassium, %	4.3
Calcium, $cmol_c$ kg^{-1}	2.8	Calcium, %	1.5
Magnesium, $cmol_c$ kg^{-1}	1.1	Magnesium, %	1.0
Sodium, $cmol_c$ kg^{-1}	0.6	Nitrogen, %	2.4

The BC and the PM were spread evenly on the soil surface and incorporated to a depth of approximately 10 cm, using a hand hoe, on 4 May 2019. Ten days later, common bean (*Phaseolus vulgaris* L. cv. BRS Netuno) was sown placing three seeds in the bottom of holes opened by hoe, spaced by 20 cm, along rows spaced by 25 cm. Manual weeding was done once a month until harvesting, on 14 August (90 days after sowing). No inorganic fertilizer or irrigation was applied during the course of the experiment. At harvest, all the aboveground biomass was cut in a 2 m^2 area in each plot and separated into straw and pods. The pods were dried, manually threshed, and the grains were weighed on a precision scale. The grain yield was adjusted to a humidity of 13% [36].

2.2. Determination of Soil Physical, Chemical, and Biological Properties

After harvest, three undisturbed and three disturbed soil samples were collected from each plot to determine physical, chemical, and biological properties. The samples were collected from the superficial soil layer (0–10 cm depth), into which the organic amendments were incorporated and where larger effects were expected. The undisturbed samples were collected using 5-cm diameter and 5-cm high cylinders (98 cm^3 volume). They were used to evaluate bulk density (BD), total porosity (TP), field capacity (FC), permanent wilting point (PWP), and plant available water (PAW). Total porosity was calculated from BD values, assuming a particle density of 2.65 Mg m^{-3}. Field capacity and PWP were obtained by the pressure plate method, using pressures of 0.01 and 1.5 MPa, respectively, and PAW was calculated as FC minus PWP [35].

The disturbed soil samples were air-dried and sieved using a 2-mm sieve and analyzed for pH, TOC, P, and K concentrations, and cation exchange capacity (CEC), following the methodologies described by Donagemma et al. [35]. Total organic carbon was determined by the C oxidation method, with potassium dichromate followed by titration of the remaining $Cr_2O_7^{2-}$ with ammonium iron (II) sulfate [37]. Phosphorus, Na^+, and K^+ were extracted using Mehlich's solution 1 (H_2SO_4 0.125 mol L^{-1} + HCl 0.5 mol L^{-1}). Phosphorus was determined by colorimetry and Na^+ and K^+ by flame photometry [35]. Calcium (Ca^{2+}), Mg^{2+}, and Al^{3+} were extracted with a KCl 1.0 mol L^{-1} solution; the first two were determined using atomic absorption spectrometry and Al^{3+} was determined by titration with NaOH 0.025 mol L^{-1}, using bromothymol blue as an indicator [35]. Potential acidity (H + Al^{3+}) was determined using calcium acetate (Ca $(CH_3OO)_2$ H_2O) at pH 7.0 [35] and CEC was calculated as the sum of bases (Ca^{2+} + Mg^{2+} + K^+ + Na^+) plus H + Al^{3+} [35].

Microbial biomass carbon (MBC) was determined using the methodology of irradiation [38], in which 20 g of irradiated and non-irradiated soil samples were extracted with 80 mL of K_2SO_4 0.5 M [39] and the C content was determined by colorimetry [40]. Enzymatic activities were determined estimating the gene expression of the main processes related to acidic phosphatase (P. Aci) and urease (Ure), according to the colorimetric analysis of the products released by the samples subjected to incubation in an adequate substrate (Sigma-Aldrich). The P. Aci was estimated according to the methodology of Eivazi and Tabatabai [41], and the Ure activity the methodology of Kandeler and Gerber [42]. Product absorbance was measured using a spectrophotometer (Libra S22, Biochrom, Cambridge, UK).

2.3. Determination of Evapotranspiration, Yield, and Water Use Efficiency

Evapotranspiration (ET) was obtained as the residual term of Equation (1), according to Silva et al. [43]:

$$\Delta S = P + I + Cr - D \pm R - ET, \quad (1)$$

where P is rainfall (mm), I is irrigation (mm), Cr is capillary rise (mm), D is deep drainage (mm), R is surface runoff (mm), ET is actual evapotranspiration (mm), and ΔS is the change in soil water storage (mm) which can be calculated as:

$$\Delta S = S_{t2} - S_{t1}, \quad (2)$$

where S_{t2} and S_{t1} are the soil water storage at the final and initial times, respectively.

Considering that the soil water content was obtained for constant soil layers from the surface (z = 0) down to the bottom of the soil depth which was measured (z = L), the storage soil moisture (S) was determined as:

$$S_L = \theta z, \quad (3)$$

where θ is the average soil layer moisture ($m^3\ m^{-3}$) and z is the thickness of the soil layer (mm).

In the field, time domain reflectometry (TDR) automatic sensors (CS616, Campbell Scientific Inc., Logan, UT, USA) were installed from 0 to 0.30-m depth to measure the soil water content. The data were read every minute and stored every 30 min in dataloggers (CR 1000, Campbell Scientific Inc., Logan, UT, USA).

In the experiment, the irrigation (I) was null and the surface runoff was obtained by rainfall data, according to Souza et al. [44]. The flux (q) of water crossing the bottom of the soil layer (deep drainage, D, or capillary rise, Cr) was obtained as follows:

$$q = -K(\theta)\nabla\psi_t, \quad (4)$$

where $K(\theta)$ is the soil hydraulic conductivity and $\nabla\psi_t$ is the vertical gradient of the total potential.

The van Genuchten [45] parametric functions were used to obtain the soil water retention function as:

$$\theta(\psi_m) = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha\psi_m)^{\mathrm{n}}\right]^{\mathrm{m}}}, \quad (5)$$

where θ_r and θ_s are residual and saturation soil water contents, respectively, in $m^3\ m^{-3}$, ψ_m is the soil matrix potential in cm of water, and α, n and m are empirical constants.

The parameters for the water retention curves were obtained by fitting Equation (5) to experimental field and laboratory data. The hydraulic conductivity for unsaturated soil, $K(\theta)$, was determined as:

$$K(\theta) = K_s S_e{}^2\left[1 - \left(1 - Se^{\frac{1}{m}}\right)^m\right], \quad (6)$$

where K_S is the saturated soil hydraulic conductivity, and S_e is the effective soil water content:

$$Se = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \quad (7)$$

The water use efficiency (WUE) was obtained by Equation (8):

$$WUE = \frac{Y}{ET}, \quad (8)$$

where Y is the yield of bean (kg ha^{-1}) that was measured in plots of 2 m^2.

2.4. Data Analysis

The normality and homogeneity of variances were respectively tested by Shapiro-Wilk and Bartlett tests. However, because some variables did not present a normal distribution, the data were subjected to the Kruskal-Wallis non-parametric test. The medians were compared using the Dunn test at the 0.05 probability level, using the R software (version 4.0.3) [46]. Spearman correlation analyses were performed between yield and other variables using the R software (version 4.0.3) [46].

3. Results

The soil amendments had no significant effects on BD, TP, FC, PWP, PAW, TOC, and MBC and also no effect on ET (Table 3, Table 4, Table 5, Table 6). The ranges of values were typical of this soil class in the region, with special notice to the low TOC concentrations (3.6 to 4.4 g kg^{-1}). The soil amendments had also no effect on soil pH and P concentration when compared to the absolute control, with exception of the treatments BC40 + PM and BC10 + PM, which significantly increased the pH and P concentration, respectively (Table 4). The soil amendments had no significant effects on K concentration and on CEC (Table 4). The treatments BC40, PM, and BC10 + PM had significant effects on P. Aci, and the treatments PM, BC10 + PM, and BC40 + PM on Ure enzymatic activities (Table 5), when compared to the absolute control. The treatments BC10 + PM and BC40 + PM had significant effects on WUE and especially on the bean yield, which was more than three times higher with the treatments BC10 + PM and BC40 + PM (Table 6), when compared to the absolute control.

Soil characteristic including pH, P, WUE, P. acid, and Ure were positively correlated with bean yield (Table 7). These correlated characteristics were those that were improved by the soil amendments.

Table 3. Effects of biochar (BC), applied at 10, 20 or 40 t ha^{-1}, and poultry manure (PM, 5 t ha^{-1}) on soil physical properties.

	Bulk Density	**Total Porosity**	**Field Capacity**	**Permanent Wilting Point**	**Plant Available Water**
Treatments	**Mg m^{-3}**			**m^3 m^{-3}**	
Control	1.21	0.54	0.20	0.16	0.04
BC10	1.19	0.55	0.18	0.14	0.04
BC20	1.22	0.54	0.20	0.16	0.04
BC40	1.25	0.53	0.20	0.17	0.03
PM	1.25	0.53	0.19	0.15	0.04
BC10 + PM	1.13	0.58	0.20	0.16	0.04
BC20 + PM	1.23	0.54	0.21	0.16	0.05
BC40 + PM	1.21	0.54	0.21	0.17	0.04
Chi^2	7.66	7.99	2.92	2.38	1.92
p-value [a]	0.36	0.33	0.89	0.95	0.96

[a] = *p*-value of the Kruskal-Wallis test.

Table 4. Effects of biochar (BC), applied at 10, 20 or 40 t ha^{-1}, and poultry manure (PM, 5 t ha^{-1}) on soil chemical properties.

	pH	**Total Organic Carbon**	**Phosphorus**	**Potassium**	**Cation Exchange Capacity**
Treatments		**g kg^{-1}**	**mg kg^{-1}**	**cmol$_c$ kg^{-1}**	**cmol$_c$ kg^{-1}**
Control	4.93	3.60	0.60	0.11	3.02
BC10	5.33	4.17	2.67	0.13	3.08
BC20	5.41	4.39	2.42	0.39	3.17
BC40	5.76	3.77	2.47	0.23	3.07
PM	5.49	3.81	17.00	0.21	3.22
BC10 + PM	5.80	3.95	36.08 *	0.34	3.59
BC20 + PM	5.76	3.88	23.22	0.27	3.37
BC40 + PM	6.04 *	3.56	17.37	0.25	3.00
Chi^2	15.00	2.19	18.92	8.52	3.08
p-value [a]	0.04	0.95	0.01	0.29	0.88

[a] = *p*-value of the Kruskal-Wallis test; * represents significant difference at alpha 0.05, by Dunn's test.

Table 5. Effects of biochar (BC), applied at 10, 20 or 40 t ha^{-1}, and poultry manure (PM, 5 t ha^{-1}) on soil biological properties.

	MBC	**Acidic Phosphatase**	**Urease**
Treatments	**g kg^{-1}**	**µg p-Nitrof. g^{-1} Soil h^{-1}**	**µg NH_4-N g^{-1} dwt 2 h^{-1}**
Control	97.67	2.36	0.27
BC10	92.71	2.59	0.66
BC20	151.04	2.88	0.37
BC40	158.40	3.11 *	0.54
PM	114.33	3.12 *	1.11 *
BC10 + PM	141.00	3.15 *	1.12 *
BC20 + PM	202.73	2.83	0.87
BC40 + PM	205.30	2.77	1.18 *
Chi^2	9.77	14.86	18.63
p-value [a]	0.20	0.04	0.01

[a] = *p*-value of the Kruskal-Wallis test; * represents significant difference at alpha 0.05, by Dunn's test.

Table 6. Effects of biochar (BC), applied at 10, 20 or 40 t ha^{-1}, and poultry manure (PM, 5 t ha^{-1}) on evapotranspiration, yield, and water use efficiency of common bean and on economic expense, income, and benefits.

	Evapotranspiration	**Yield**	**Water Use Efficiency**	**Expense**	**Income**	**Benefit**
Treatments	**mm**	**kg ha^{-1}**	**kg ha^{-1} mm^{-1}**		**US$**	
Control	350	553	1.6	270	691	421
BC10	349	911	2.6	2270	1139	−1131
BC20	347	1124	3.2	4270	1405	−2865
BC40	345	1379	4.0	8270	1724	−6546
PM	354	1828	5.2	460	2285	1825
BC10 + PM	350	2515 *	7.2 *	2460	3144	684
BC20 + PM	347	1799	5.2	4460	2249	−2211
BC40 + PM	349	2398 *	6.9 *	8460	2998	−5463
Chi^2	3.13	17.79	18.05			
p-value [a]	0.87	0.01	0.01			

[a] = *p*-value of the Kruskal-Wallis test; * represents significant difference at alpha 0.05, by Dunn's test.

Table 7. Spearman's rank-order correlation coefficient between yield of common bean and pH, phosphorus (P) and potassium (K) concentrations, cation exchange capacity (CEC), total organic carbon content (TOC), evapotranspiration (ET), water use efficiency (WUE), field capacity (FC), permanent wilting point (PWP), bulk density (BD), total porosity (TP), microbial biomass carbon (MBC), and acidic phosphatase (P. acid) and urease (Ure) activities. (n = 8).

Property	Coefficient	Property	Coefficient
pH	0.8809 **	FC	0.1557
P	0.7143 *	PWP	0.2994
K	0.5238	BD	−0.3832
CEC	0.4048	TP	0.3832
TOC	0.0964	MBC	0.5952
ET	0.0491	P. acid	0.6905 *
WUE	0.9940 **	Ure	0.9048 **

*, ** represent significant correlation at alpha 0.5 and 0.01, respectively.

4. Discussion

The fact that the application of BC and PM, isolated or combined, did not enhance the soil physical properties, including BD, TP, FC, PWP, and PAW, could be partly attributed to the texture of the soil in the experimental area. The effects of these organic amendments are greater in coarse-textured soils [27,47] and the soil in the experimental area is classified as a sandy clay loam (Table 1). Adekiya et al. [22] found positive effects of BC and PM on physical properties of a Luvisol with 76% sand and Agbede et al. [23] found that BC and PM treatments significantly reduced BD and increased TP and soil water content, also in a Luvisol, but with 92% of sand. The effects of the amendments are also influenced by their particle size and the 2 mm used in the current study may have been too coarse. Głąb et al. [48] reported positive effects on soil physical attributes using particle size smaller than 0.5 mm. The short period (three months) between application of the amendments and soil sample may have also precluded more extensive changes in these soil properties [49,50]. Most studies describing positive soil structure evolution with BC amendment claim better soil aggregation due to enhanced microbial activity, the presence of mycorrhizal hyphae [50,51]. Finally, the applied amendments correspond to relatively small proportions of the total soil volume and mass of the sampled layer and, consequently, their influence on physical properties tends to be limited.

BD and TP are associated with soil texture and also with soil structure, i.e., aggregation and stability, which are related with TOC [52]. Yang and Lu [53] found that the soil aggregation and stability could be partly related to the increased TOC in the BC-amended soils. However, in our study, the TOC was not significantly influenced by the application of the soil amendments (Table 4); thus, this can also explain the absence of significant effects of the amendments on BD and TP in this short-term field experiment.

The soil pH and P concentration, as well as enzyme activities were positively affected by the application of the soil amendments (Tables 4 and 5), contrasting to the absence of effects on the physical properties. These effects are particularly important in acidic soils with low initial soil fertility status. Du et al. [54] reported that PM application increases soil pH and Adekiya et al. [22] and Agbede et al. [23] argued that manure increases soil pH due to ion exchange reactions which occur when the terminal OH^- of Al^{3+} or Fe^{2+} hydroxyl oxides are replaced by organic anions, such as malate, citrate, and tartrate, originated from the decomposition of the manure. BC also increases soil pH due to its high pH (9.8), caused by the alkaline ash in its composition [18], which includes Ca and Mg oxides and K oxides, hydroxides, and carbonates [55].

The decrease in soil acidity may have promoted an increase in P availability (Table 4). Glaser and Lehr [56] found that the addition of BC significantly increased P availability, up to a factor of 4.6, independently of the woodstock used for BC production. The BC liming and fertilization effects, especially on nutrient-poor and acidic soils, results in higher crop yields [57], as obtained in our study. Du et al. [54] performed a meta-analysis to determine the effect of several manure types (e.g., pig, cattle, sheep, cow, chicken, livestock and farmyard) on soil properties and found that manure application also increases available P and K, promoting higher yields, more pronounced under warm and humid climates. The high correlation of the soil chemical and biological properties with yield indicates that the improvement in these properties may be partially responsible for the yield increase. The increase in pH and in nutrient availability may have also been contributed to the alteration in the Ure and P. acid activities, which are crucial for soil health due their role in organic matter decomposition, being considered the most sensitive indicator of soil changes [58].

The most important effect certainly was the increase in bean yield (Table 5). The average bean yield in this study region is low, around 900 kg ha^{-1} [59], and it is attributed to the sandy soils where the culture prevails, which have low fertility and low water retention capacity [11]. The combined application of PM and BC increased the yield by 355%. In conjunction with the low income of farmers, the low availability of cattle manure [13], and the good availability of PM and of agricultural wastes for the production of BC [18,60], the application of this combination can be a viable alternative to increase bean yield in the region.

The production costs of one hectare of bean, amended with 5 t ha^{-1} of PM, in the study region, are approximately $460 [59], and considering that the price of bean is $1.25 kg^{-1}, the application of PM would have a return of approximately $1800 ha^{-1}. The BC cost is variable, but considering the value of $200 ton^{-1} [61], the treatment BC10 + PM would have a return of approximately $680 ha^{-1}, i.e., lower than that of PM alone. However, as BC is a source of recalcitrant carbon with a long mean residence time (several decades to several centuries) [21], it can promote positive effects on soil properties for many years.

5. Conclusions

The use of biochar (BC) and poultry manure (PM) had contrasted consequences on soil properties. Soil properties like BD, water holding capacity or CEC were unaffected by the amendment of BC in the application rates chosen in this study (10, 20, 40 t ha^{-1}). Different amounts of BC amendments or longer experimental periods might have had more significant impacts and further investigations are recommended to study long-term effects. However, this one-year field experiment demonstrated the efficiency of the combination of BC and PM amendments in improving soil chemical and biological properties. The combined application of 10 t ha^{-1} of BC and 5 t ha^{-1} of PM can be a viable management practice for smallholder farmers in the Brazilian sub-humid region since it increases P concentration, enzymatic activities, and water use efficiency and, particularly, it increases yields compared to the application of either BC or PM alone.

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