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Screening of High-value Vegetable Species under Fortified Biochar Soil Treatments

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Abstract. **Farmers in Timor-Leste are currently attempting to grow vegetable crops in paddy fields areas after harvest rice. However, typical productivity and profitability are very low. Rice husk biochar fortified with urea and superphosphate has been shown to be an effective fertilizer for vegetable production. However, the rates of fortified biochar applications used in research trials are very high (between 20 and 30 t·ha^{-1}). This high rate is not realistic for farmers involved in vegetable production because the average rice yields in Timor-Leste only range from 1.5 to 3 t·ha^{-1}·year^{-1}. Where are farmers going to find high volumes of rice husk biochar? Therefore, the present study was designed to test low, achievable, and affordable rates of rice husk biochar in combination with nitrogen and phosphorus, which is known as fortified biochar, to increase the production of high-value vegetables in a vegetable–rice cropping sequence. In addition, a gross margin analysis was conducted to determine if the low rates are economically significant. This study was undertaken in the rice growing area of Maliana irrigation system, Timor-Leste, in 2020. The experiment used a split-plot design for testing the performance of valuable vegetable species with fortified biochar application. The main plot included the rate of fortified biochar with three levels of treatments: 0, 1, and 3 t·ha^{-1}. The sub-plots included eight vegetable species (pokchoi, cucumber, capsicum, cabbage, tomato, eggplant, rockmelon, and watermelon). The results of the study showed that the application of fortified biochar significantly increased vegetable yields between 45% and 171% at an application rate of 1 t·ha^{-1} and between 137% and 424% at an application rate of 3 t·ha^{-1} compared with the control treatment (no fortified biochar). In addition, the results of the gross margin analysis indicated that the application of 3 t·ha^{-1} fortified biochar provided the higher gross margin of between US $135 and US $5000 per crop per year (depending on species) for one-tenth of a hectare compared with the control. The study findings demonstrated that even very low doses of fortified biochar significantly improved vegetable yields and farm household income in the vegetable phase of a vegetable–rice cropping sequence.**

Rice (*Oryza sativa* L.) is the leading staple food for nearly half the world's population (Mohidem et al. 2022; Muthayya et al. 2014), and it accounts for 21% of the global calorie intake while using 11% of global cropland (FAOSTAT 2019). Global rice consumption, driven by population and economic growth, is projected to grow from 480 million tons of milled rice in 2014 to nearly 550 million tons by 2030 (Kumar and Yadav 2020). However, several issues have been identified that will hamper the sustainability of rice production to meet the global demand in the future. These issues include costs of rice production that are steadily increasing while the price in the market remains low from year to year (Mottaleb and Mohanty 2015). This high cost of rice production and low rice prices in the market have impacted the financial ability of smallholder farmers to invest in agricultural inputs to modernize rice production systems (Kumar et al. 2018; Van Nguyen and Ferrero 2006). Consequently, rice production is low and productivity ranges from 2.0 to 3.0 t·ha^{-1}·crop^{-1}·year^{-1} (TOMAK 2016), although many growers experience productivity less than 2.0 to 3.0 t·ha^{-1}·crop^{-1}·year^{-1}.

The high cost of rice production, with low rice yields and prices, result in declining household profitability (Reis et al. 2022). These factors are hampering issues for farmers and can cause them to choose to not to grow a second crop of rice even in irrigated paddy field areas (Fox et al. 2002). Many smallholder farmers fallow their land in the dry season and search for new jobs in cities to make money that they send to their parents to reinvest in rice production in the wet season (Agarwal and Agrawal 2016).

However, these issues have also increased the interest of some farmers in diversification by complementing rice with other crops, such as high-value vegetable crops (He et al. 2023; Hufnagel et al. 2020). This is because the intensification and diversification of cropping (including cropping of high-value vegetables) are receiving more attention because of the availability of short-duration crop seed, high market demand, and high prices (He et al. 2024). Growing high-value vegetable crops in the dry season increases funding for labor wages and generates household income to sustain subsequent rice production in the wet season (Avasthe et al. 2020; Ekka et al. 2019; Kumar et al. 2018). The income generated by vegetables can support smallholder household income for poor farmers in paddy field areas (Paudel 2016).

Similarly, high-value vegetable crops have been gaining importance in Timor-Leste, as measured in diet diversification, because vegetables are being consumed regularly by the Timorese population (Bonis-Profumo et al. 2021; Johnston and Aniceto 2013). Most of the population earns less than US $2 per day (Lucas et al. 2023). Therefore, many Timorese cannot afford to regularly buy fish, meat, and other more expensive products (Bonis-Profumo et al. 2021). As a result, most of the Timorese population tends to purchase vegetables rather than meat or fish. The Timor-Leste government has given high priority to developing horticultural crops, as formulated in the Strategic Development Plan 2011–30 (Government of Timor-Leste 2011). As found elsewhere, growing high-value vegetable crops in the dry season after harvesting rice may provide farmers with income to reinvest in rice production in the subsequent wet season (Avasthe et al. 2020; Ekka et al. 2019; Kumar et al. 2018). These systems are critical for achieving future food and nutrition for the burgeoning Timorese population (Minot and Roy 2007; TOMAK 2016).

However, the yield of growing vegetable crops in paddy field areas in Timor-Leste is generally very low, and the rice-based system is defined as low-input–low-output. In recent decades (since 1980), limited external inputs have been applied to the soil, even though it produces a rice crop every year. Consequently, each year, essential elements for crop growth are harvested and carried away with the rice grain (Williams et al. 2019). With a rice yield of 5 t·ha^{-1}, approximately 90 to 100 kg nitrogen (N), 20 to 30 kg phosphorus (P), and 60 to 80 kg potassium (K) are removed from the rice field (Sukristiyonubowo 2007); however, the rice yields in Timor-Leste are typically half that (TOMAK 2016). Nutrient removal from rice fields is even higher when the straw is removed and burned or used as animal feed, as commonly practiced by Timorese farmers

(Sukristiyonubowo 2007; Williams et al. 2019).

Combining rice husk biochar and inorganic N and P fertilizer to produce fortified biochar has been trialed for existing vegetable–rice cropping sequences in Timor-Leste to improve soil fertility, crop productivity, and income generation (Gomes et al. 2023). Several studies have identified that the application of fortified biochar doubles chili pepper, sweet pepper, tomato, carrot, phaseolus bean, yardlong bean, and soybean yields compared with control treatments (Williams et al. 2023). The application of fortified biochar enhances the availability of N (Li et al. 2019) and levels of P, K, and zinc (Zn) in crops (Prakongkep et al. 2013; Williams et al. 2023). This positive impact of fortified biochar application is considered a pivotal innovation to improve soil nutrients for crop production (Gul and Whalen 2016; Williams et al. 2023). However, recent biochar trials conducted in Timor-Leste used high rates of biochar at 20 to 30 t·ha^{-1} (da Costa Guterres et al. 2018, 2019). This high volume of biochar utilization is unlikely to be widespread for rice husk biomass because the average rice yields in Timor-Leste only range from 1.5 to 3 t·ha^{-1}·year^{-1} (Fanzo and Bonis-Profumo 2019).

Fortified biochar in Timor-Leste has been developed by a consortium of research partners, including Universidade Nacional Timor Lorosa'e (UNTL), the Ministry of Agriculture and Fisheries of Timor-Leste, and the Australian Centre for Agricultural Research. The standard formulation of fortified biochar consists of low rates of rice husk biochar with 2% N (as urea) and 1% P_2O_5 (as SP-36). The combined application of biochar with fertilizer is gaining acceptance by farmers and extension agencies as increasing evidence that it improves soil fertility and crop yield elsewhere and locally is found (Bai et al. 2022; da Costa Guterres et al. 2019; Williams et al. 2019, 2023).

Other studies have shown that fortifying biochar increases yields compared with the application of biochar alone (Bai et al. 2022; Ndoung et al. 2021), including in Timor-Leste (Gomes et al. 2023). This study was a rate trial for fortified biochar, not a comparison of the impacts of biochar and the amendments (i.e., urea and superphosphate). Furthermore, unlike previous studies that used high doses of fortified biochar and focused on maximizing yield, this study focused on low rates that match the volume and composition of raw materials available to most smallholder farmers in paddy field areas in Timor-Leste. The impact of these low rates of fortified biochar on soil nutrients, vegetable production, and economic return were evaluated in the context of farming in Timor-Leste.

This study aimed to measure the response of a range of high-value dry-season vegetable species to fortified biochar, measure the impact of fortified biochar on soil properties, and measure the impact of fortified biochar on the household profitability of growing each vegetable species. This study was conducted in situ on private farmland in a significant vegetable-producing area in Timor-Leste and at low rates of treatment levels of fortified biochar to represent the conditions achievable by farmers. These findings may be used to inform farmers' decisions about vegetable selection and the use of soil amendments using low doses of biochar, N, and P.

Materials and Methods

Research site. This research was undertaken at the Maliana irrigation system, Timor-Leste, from Jul to Dec 2020. Maliana is considered one of the main rice field areas in Timor-Leste. Rice field areas in the Maliana irrigation system consist of 3200 ha, which are used for rice production in the wet season, and one-tenth of this land is used for growing alternative crops in the dry season (Ministry of Agriculture and Fisheries 2015). Because of its potential for rice and vegetable production, the Government of Timor-Leste and the Japan International Cooperation Agency have rehabilitated two irrigation schemes to enable year-round production of rice and vegetables (Japan International Cooperation Agency 2017).

Maliana is located 149 km southwest of Dili, the national capital, and is located just a few kilometers from the border with Indonesia (lat. 8°58′21.4″S, long. 125°11′48.5″E) (Fig. 1). The mean annual rainfall ranges from 1000 to 1500 mm yearly, with 94% of the rainfall occurring in the wet season between October and March; the mean temperature is approximately 24 °C (Fox et al. 2002). The slope of the study site is 0% to 0.3%, and the elevation is 188 m. Soil is classified as a tropofluvent, derived from old alluvial material (Garcia and Cardoso 1978), with shallow and rocky soil on surrounding higher ground (Thompson 2011). The soils are a mixture of alluvial sandy loam and clay of moderate fertility with pH of 5 to 7 (Garcia and Cardoso 1978; Howeler et al. 2002). The vegetation of the fallow field in the study site is dominated by short grasses and herbaceous vegetation such as feather top rhodes grass (*Chloris virgata*), jungle rice (*Echinochloa colona*), barnyard grass (*Echinochloa crus-galli*) and rice flat sedge (*Cyperus iria*), as found in other parts of paddy field areas in Indonesia (Ismail and Abdullah 2020). The study was performed on an active farm and on land made available by a local farmer. This context was chosen to promote farmer engagement for extension purposes.

Plant materials. Eight vegetable and fruit species were included in this study. They were chosen based on their high demand in the national supermarkets, likely profitability for farmers, local seed availability, and existing farmer preferences for cropping. These eight high-value species were watermelon (*Citrullus vulgaris schard*), rockmelon (*Cucumis melo var. cantalupensis*), capsicum (*Capsicum annuum L.*), cucumber, tomato (*Solanum lycopersicum*), cabbage (*Brassica oleracea*), pokchoi (*Brassica rapa subsp. Chinensis*), and eggplant (*Solanum melongena*). All seeds (except for capsicum) were purchased from agrochemical shops in Timor-Leste. Capsicum seeds were purchased from Australia because capsicum seeds were not widely sold in local markets at the time of the trial despite the high market value.

Biochar production from rice husk. Biochar used for this experiment was produced from rice husk collected from a rice milling center in Maliana using a chimney pyrolysis process (Fig. 2). This method required a chimney made of metal mesh (flyscreen) rolled into a cylinder with a diameter of 0.4 m and length of 1.2 m. The chimney was stood on a sheet of roofing iron, and a small fire using dry palm leaves was lit at the chimney base. Then, approximately 150 kg of rice husk was piled around it so that the lower part of the chimney was subsequently buried in rice husks; only the chimney protruded out of the rice husk heap. As the fire front burned from the center to the outer parts of the pile, the rice husk was burned to charcoal, and the resulting gases were released through the chimney. The process ended when the fire front reached the outer edge of the rice hulls. As the fire front consumed all the oxygen, the rice hull biochar between the fire front and the chimney did not burn; instead, it smoldered, leaving just the charcoal. A pyrolysis temperature of approximately 400 °C (Williams et al. 2023) was achieved, and 50 kg of biochar was completed after 4 h. Then, the biochar was extinguished and immediately cooled with water before being applied to the experimental plots.

Formulation of soil treatments. This experiment was a two-way factorial combination of eight vegetable species and three rates of fortified biochar treatment. The fortified biochar treatment rates were 0, 1, and 3 t·ha^{-1} (Table 1).

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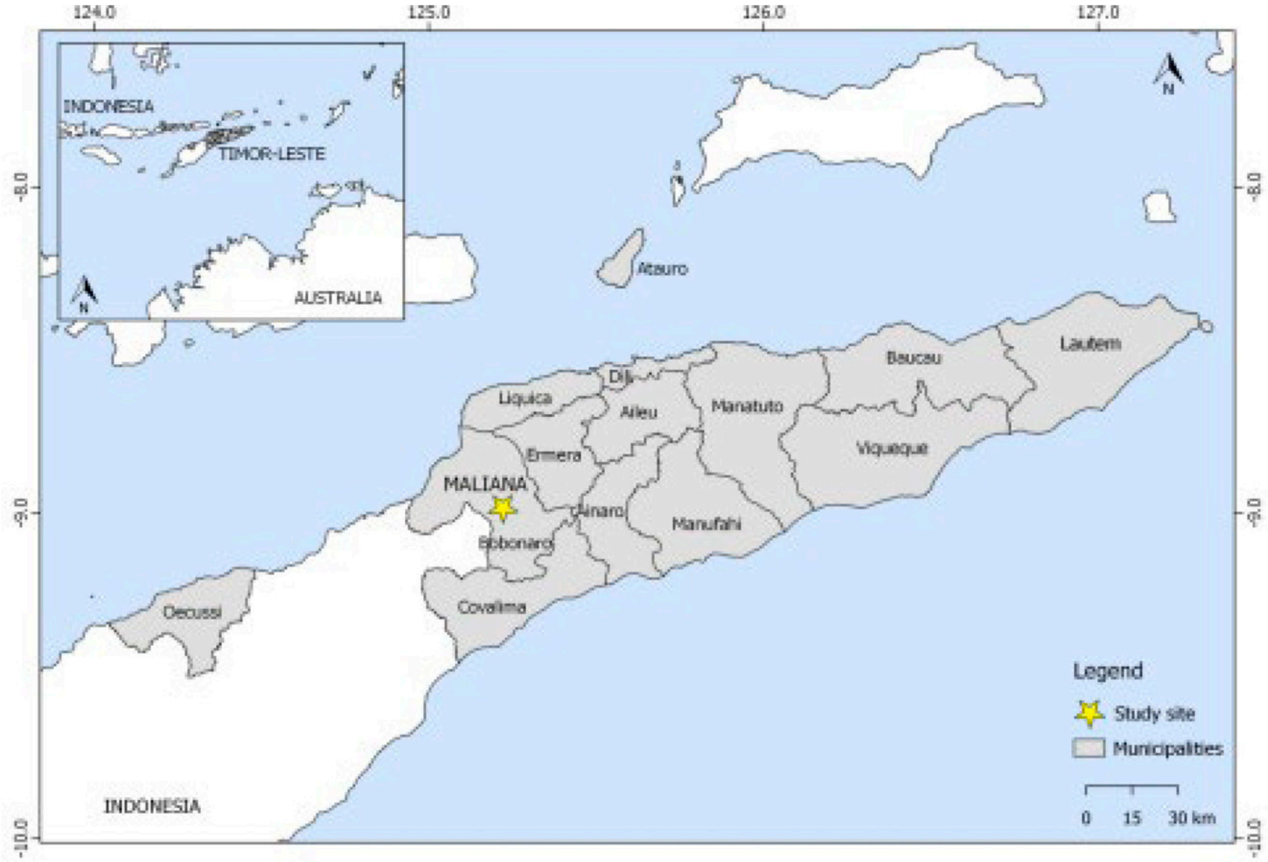

Fig. 1. The location of the research site is indicated by the yellow star.

The following equation was used to calculate the N (urea), P (SP-36), and biochar application rates.

$$Amendment\ rate = plot\ size \times dose\ of\ amendment \times factor\ of\ correction\ for\ fertiliser\ (N\ and\ P)$$

where the factor of correction is the percentage of N or P in the source product. Urea includes 45% N, and SP-36 includes 36% P.

Experimental design. A split plot design with two factors, vegetable species and fortified biochar treatments, was chosen. The main plot included the application rates of fortified biochar and the sub-plot included cabbage, capsicum, cucumber, eggplant, pokchoi, rockmelon, tomato, and watermelon. All treatments were replicated four times, resulting in a total of 96 observation plots. Plots were 3 m × 3 m (9 m^2). Each plot was separated by 0.50 m, and the blocks were separated by 1 m. This study was conducted in an active farming district on land provided by local farmers. Hence, the plot size and block spacing were determined by the availability of land at the study site.

Agronomy practices. Seedlings with a height of approximately 15 cm with three to five leaves at 30 days were transplanted on experimental plots at planting time at a depth of 2 cm; a single seedling per hill was maintained. Plant densities varied among species, based on growth form, as follows: pokchoi, 25 cm × 25 cm; capsicum, 40 cm × 40 cm; cabbage, cucumber, rockmelon, and watermelon, 50 cm × 50 cm; and tomato and

Fig. 2. Biochar production using the chimney method (source: AI-Com Timor-Leste).

Table 1. Treatment levels of fortified biochar ($t \cdot ha^{-1}$) for vegetable species production.

N ($kg \cdot ha^{-1}$)	P ($kg \cdot ha^{-1}$)	Biochar ($kg \cdot ha^{-1}$)	Treatment rates of fortified biochar ($t \cdot ha^{-1}$)
0	0	0	0
20	10	1000	1
60	30	3000	3

eggplant, 60 cm × 60 cm. Biochar and inorganic fertilizers were mixed before application and applied around the base of each seedling at planting. Fortified biochar was applied when the seedlings were transplanted. The crop was irrigated by hand when needed. Transplanted seedlings were observed regularly for up to 2 weeks, and any dead or damaged seedlings were replaced. Weeding was done by hand as required, and plant-protective measures including Regent 200 g/L (active ingredient fipronil) were applied for insect control. General observations regarding the presence of insect pests and diseases were made at an interval of 7 d, starting from 15 d after sowing and ending at physiological maturity.

Plant growth and yield measurement. Plant height and canopy cover were measured, at 2, 4, and 6 weeks after transplanting. Height was measured from the stem base at the soil surface to the tip of the longest leaf of the plant from five sample plants. In the case of vines (watermelon, rock melon, and cucumber), vine length was measured. Canopy cover was measured using an Android application (*Canopy Cover Free*) at 2, 4, and 6 weeks after transplanting. The phone was held horizontally 1 m above the plots to measure the canopy cover. At this height, the application sensed an area of approximately 2.2 m^2. The canopy cover percents were logged on a mobile phone (MODEL oppo A5S). Three independent measurements were collected within each plot at each monitoring time.

Yields of whole plots were recorded at the time of harvest. The following parameters of the yield and yield components were recorded: counts of the number of fruits per plant (except for cabbage and pokchoi) as well as total yield (simple weight after harvest of the fruits or heads divided by the harvested area).

Measurement of unsaleable and saleable yields. After recording yields per replicate, produce of each species for each treatment were pooled across replicates in the field and homogenized in the shade house before being cleaned, sorted, and graded for sale. Sorting and grading were conducted at the farm gate based on the buyer's and consumer's preferences from among produce grown under the three treatments (control, fortified biochar 1 $t \cdot ha^{-1}$, or fortified biochar 3 $t \cdot ha^{-1}$). Vegetables that were not purchased or that were excluded during sorting and grading were considered losses (although they were used for family consumption or feeding animals). We also identified the main causes of this unsaleable yield, which included low-quality produce with a small size or discoloration that may not meet with market standards.

Analysis of soil pH, nutrients, and particle size. Soil samples were collected just after the harvest, and only from tomato and cabbage plots, on 10 Nov 2020. These samples were analyzed to determine soil pH, respiration, and a range of Mehlich 3 extractable elements. Soil samples were taken from underneath the plant canopy. Three replicate sub-samples were collected from each plot. The replicates were pooled in the field and homogenized in the laboratory to form a composite sample for each plot. Soil was taken from 0 to 15 cm for each sample using a hand auger with diameter of 5.5 cm. Soil samples were air-dried for 2 weeks, followed by sieving through a 2.0-mm sieve and kept in polyethylene bags. The dry samples were stored in the sample bag at room temperature.

Soil samples were analyzed to determine pH and Olsen P in the Ministry of Agriculture and Fisheries soil laboratory in Dili. Soil pH (H_2O) was measured in a 1:5 solution using a pH probe. Approximately 200 g of nonground sample was sent to the University of Western Australia laboratory for analysis. At the University of Western Australia laboratory, the samples were steam-autoclaved at 121 °C for 30 min to meet quarantine requirements. After autoclaving, soils were stored in a cool room at ambient temperature for 1 month before further analysis. Concentrations of extractable aluminum (Al), calcium (Ca), copper (Cu), iron (Fe), K, magnesium (Mg),

Table 2. Critical levels of plant essential elements values based on critical points reported by Haefele et al. (2024) and Rayment and Lyons (2010). These critical levels of plant nutrients were compared with the results of soil nutrients of control treatments in this study.

Soil nutrients	Low ($mg \cdot kg^{-1}$)	Medium ($mg \cdot kg^{-1}$)	High ($mg \cdot kg^{-1}$)	Source
Phosphorus	5–15	16–30	30–50	Haefele et al. (2024)
Potassium	90–190	191–600	600–900	Haefele et al. (2024)
Sulfur	5–10	11–40	41–50	Haefele et al. (2024)
Magnesium	22–41	42–71	72–148	Haefele et al. (2024)
Calcium	307–503	504–699	700–895	Haefele et al. (2024)
Zinc	1.0–10	10–50	>50	Haefele et al. (2024)
Copper	0.5–1.0	1.0–20	>20	Haefele et al. (2024)
Boron	1.0–1.5	1.5–20	>20	Haefele et al. (2024)
Iron	60–80	80–300	300–400	Haefele et al. (2024)
Manganese	60–100	100–300	300–500	Haefele et al. (2024)
SOC (% C by weight)	2–4	4–10	10–20	Rayment and Lyons 2010
Soil N (% N oven-dried weight)	0.05–0.15	0.15–0.25	0.25–0.50	Rayment and Lyons 2010

C = carbon; N = nitrogen; SOC = soil organic carbon.

Table 3. *F* value from the analysis of variance (ANOVA) of the effect of the fortified biochar rate on plant height/length for each vegetable species.

Source of variation	*df*	Cabbage	Capsicum	Cucumber	Eggplant	Pokchoi	Rockmelon	Tomato	Watermelon
Fortified biochar rate	2	100***	75***	1629***	3746***	22**	34***	3.9	77.3***
Linear response to fortified biochar rate	1	197***	149***	3257***	5065***	45***	66***	7.8*	119***
Quadratic response to fortified biochar rate	1	3.9	0.3	1.3	2427***	0.01	1.3	0.02	35.6***
Residual	6	1.0	1.0	0.5	2.0	6.0	4.0	5.3	1.5
Time	2	109***	344***	581***	21386***	253***	7153***	78.8***	587.1***
Time × fortified biochar rate	4	1.74	21***	157***	1833***	1.3	24***	4.8*	30.4***
Time × linear response to fortified biochar rate	2	0.97	40***	312***	2540***	2.0	47***	9.4*	44.2***
Time × quadratic response to fortified biochar rate	2	2.51	2	1.1	1126***	1.0	2.0	0.2	16.6***
Residual	18								
CV (%)		13.3	9.7	8.9	1.4	8.5	4.0	27.0	12.4

Refer to mean values presented in Fig. 3. * $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$. Species were analyzed separately, with significance indicated for each species among treatments, not in comparison with other species.

df = degrees of freedom.

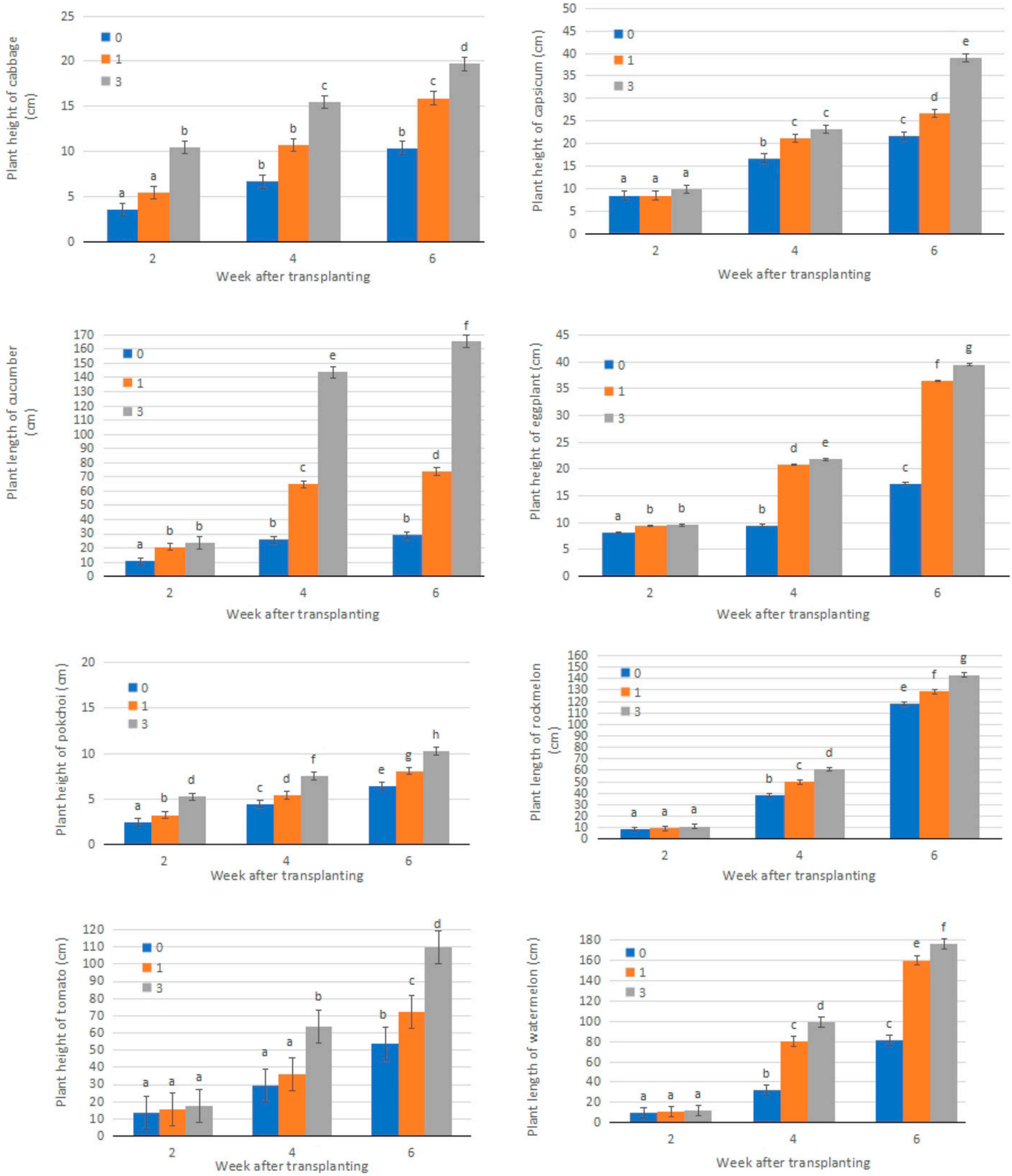

Fig. 3. The responses of plant height and plant length (cm) to fortified biochar (FB) rates at weeks 2, 4, and 6 for each tested vegetable species after transplanting. Blue boxes are the control, orange boxes are fortified biochar 1 t·ha^{-1} with 2% nitrogen (N) and 1% phosphorus (P), and silver boxes are fortified biochar 3 t·ha^{-1} with 2% N and 1% P.

sodium (Na), P, sulfur (S), and zinc (Zn) were determined using Mehlich 3 extractions with inductively coupled plasma optical emission spectroscopy, and total carbon (C) and N were measured by dry combustion in a combustion analyzer (Elementar, Langenselbold, Germany) (Shahane et al. 2020). The extractable nutrient levels measured in this study were compared with the critical levels reported by Haefele et al. (2024) and Rayment and Lyons (2010) (Table 2) to benchmark our results.

Analysis of soil respiration. Soil respiration measurements were conducted at PT Biodiversitas Bioteknologi Bogor Indonesia by using the titration method. One hundred grams of wetted soil was placed in a 1-pint Mason jar along with a vial of 10 mL of

1 M KOH. These alkali traps were changed and titrated on day 7. Unreacted alkali in the KOH traps was back-titrated with 1 N HCl to determine CO_2-C6. Basal soil respiration was calculated by subtracting the cumulative of 7 d of CO_2-C (Haney et al. 2008).

Statistical analysis of treatment effects. Plot level data (e.g., yield, soil variables) were analyzed using an analysis of variance (ANOVA) of the split plot design. Data were analyzed using GENSTAT statistical software (23rd edition, A VSNi product).

If the variation between treatments was significant ($P \leq 0.05$), then post hoc testing of differences between means was undertaken using the Bonferroni test for multiple comparisons. Data regarding plant height and canopy are presented in graphs with annotations based on the Fisher's least significant difference test because the Bonferroni test was not appropriate for these data. Before the analysis, all data were checked for assumptions of normality by using Levene tests for homogeneity and Levene tests for variance stability.

In this study, multilinear regression was used to explain why some species responded to fortified biochar more than others. The significant interaction between fortified biochar treatments and vegetable yields was explored using regression. The response variate was yield ($t{\cdot}ha^{-1}$). The maximal model was:

$$\textit{Biochar application rate} + \textit{crop duration} + \textit{Canopy cover at 2 weeks after planting} + \textit{Vegetative OR Reproductive}$$

Economic analysis. The saleable yield was used to calculate the partial budget to evaluate the financial return. The objective of the partial budget was to calculate the marginal changes in return for each vegetable species in response to fortified biochar application. Based on the increase in yield, cost of fertilizer, and market price of the products, a dollar value was given to the increase in production. The following equations were used to calculate the partial budget for the economic analysis:

$$\textit{Total extra cost of production} = \textit{Doses of the applied fortified biochar} \times \textit{cost of fortified biochar} \times 1000$$

$$\textit{Observed extra yield } (t{\cdot}ha^{-1}) = \textit{Yield of treated plots} - \textit{yield of control plots}$$

$$\textit{Extra income from treatments } (\$ {\cdot}ha^{-1}) = \textit{Price of the products} \times \textit{extra yield} \times 1000$$

$$\textit{Extra kg yield per kg of fortified biochar } (kg{\cdot}kg^{-1}) = \textit{Extra yield}/(\textit{doses of applied fortified biochar})$$

$$\textit{Value per input } (\$ {\cdot}kg^{-1}) = \textit{Extra income}/(\textit{doses of the applied fortified biochar} \times \textit{cost of fertilizers} \times 1000).$$

$$\textit{Value per kg input } (\$ \textit{of product}/\textit{kg fortified biochar}) = \textit{Extra income}/(\textit{doses of fortified biochar}/1000).$$

The profitability calculation was measured by using the gross margin, which was calculated for each combination of vegetable and fortified biochar application. The gross margin in this study was determined using the following equation (NdaNmadu and Marcus 2013):

$$GM = TR - TVC$$

where *GM* is the gross margin, *TR* is the total revenue, and *TVC* is the total variable cost.

Data required for gross margin calculations were obtained from all data recorded from the saleable yield of vegetable species ($t{\cdot}ha^{-1}$), farm gate prices of the products, and cost of production, which consists of the cost of required labor and cost of the inputs, which were recorded in this study.

Results

Vegetables growth and yield

Growth. Overall, the results of the ANOVA indicated that the plant height for each vegetable species was significantly different ($P < 0.001$) among the levels of treatments at 2, 4, and 6 weeks after transplanting (Table 3).

Without soil amendment, all vegetable species were shorter (Fig. 3). In the presence of fortified biochar 1 $t{\cdot}ha^{-1}$, vegetable plant heights significantly increased compared with control treatments (Fig. 3.). In the presence of fortified biochar 3 $t{\cdot}ha^{-1}$, the plant height significantly increased compared with 1 $t{\cdot}ha^{-1}$ treatments (Fig. 3).

The height of vegetative crops of cabbage and pokchoi and nonvegetative crops cucumber and eggplant responded significantly to treatments at 2, 4 and 6 weeks after transplanting. Tomato, capsicum, rockmelon, and watermelon showed a significantly high height response to fortified biochar at 4 and 6 weeks after transplanting (Fig. 3).

The results of the ANOVA of plant canopy cover for each vegetable species also showed significant ($P < 0.001$) differences in the levels of applied fortified biochar at each observation (Table 4). The response of capsicum overall differed from that of the other species.

In the presence of fortified biochar at 1 $t{\cdot}ha^{-1}$, the canopy cover of all vegetable species, except capsicum, significantly increased throughout the growing season compared with the control treatment (Fig. 4). In the presence of fortified biochar at 3 $t{\cdot}ha^{-1}$, canopy cover significantly increased again compared with the lower dose and the control treatments for most species throughout the growing seasons, except for capsicum, which only differed significantly from control treatments at the 6-week stage (Fig. 4). Overall, the canopy responses among species were similar to plant height patterns.

Crop duration (time from transplant to harvest) varied with species. The vegetable species with the shortest duration was pokchoi (45 d), followed by cucumber (60 d). The duration for both rockmelon and watermelon was 70 d, and that for both eggplant and tomato was 75 d. The vegetable species with the longest duration were cabbage and capsicum (both 95 d) (Table 5).

Yield response to fortified biochar. The results of the ANOVA indicated that the yield of each vegetable species was significantly ($P < 0.001$) affected by the application of fortified biochar treatments (Table 6). In addition, the ANOVA indicated that the yields of all vegetable species increased linearly, and most (all except tomato, pokchoi, and capsicum) had a quadratic response to fortified biochar treatments.

Overall, the results indicated that applying fortified biochar at 1 $t{\cdot}ha^{-1}$ significantly increased each vegetable yield by an average of 98% compared with control. As the rate of fortified biochar was increased to 3 $t{\cdot}ha^{-1}$, the yields of cabbage and rockmelon increased to three-times that of the control. The

Table 4. *F* value from the analysis of variance (ANOVA) of the effect of fortified biochar rate on canopy cover for each vegetable species.

Source of variation	*df*	Cabbage	Capsicum	Cucumber	Eggplant	Pokchoi	Rockmelon	Tomato	Watermelon
Fortified biochar rate	2	5838***	1.5	254***	12457***	1643***	16.7**	14.4**	32117***
Linear response to fortified biochar rate	1	10587***	3.1	422***	23494***	2720***	30**	24.1**	61367***
Quadratic response to fortified biochar rate	1	1089***	0.01	85***	1419***	566***	3.3	4.6	2867***
Residual	6	0.9	3.8	3.5	0.3	1.3	3.2	3.3	0.5
Time	2	11739***	44.5***	2439***	14290***	1656***	114***	205***	39212***
Time × fortified biochar rate	4	499***	1.4	65***	252***	47***	6.2**	11**	840***
Time × linear response to fortified biochar rate	2	822***	1.3	59***	402***	73***	4.5*	16**	679***
Time × quadratic response to fortified biochar rate	2	176***	1.5	71***	102***	24***	7.8**	5.6*	1001***
Residual	18								
CV (%)		2.2	44.2	4.8	2.2	3.6	18.8	19.4	1.0

Refer to mean values presented in Fig. 4. * $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$. Species were analyzed separately, with significance indicated for each species among treatments, not in comparison with other species.
df = degrees of freedom.

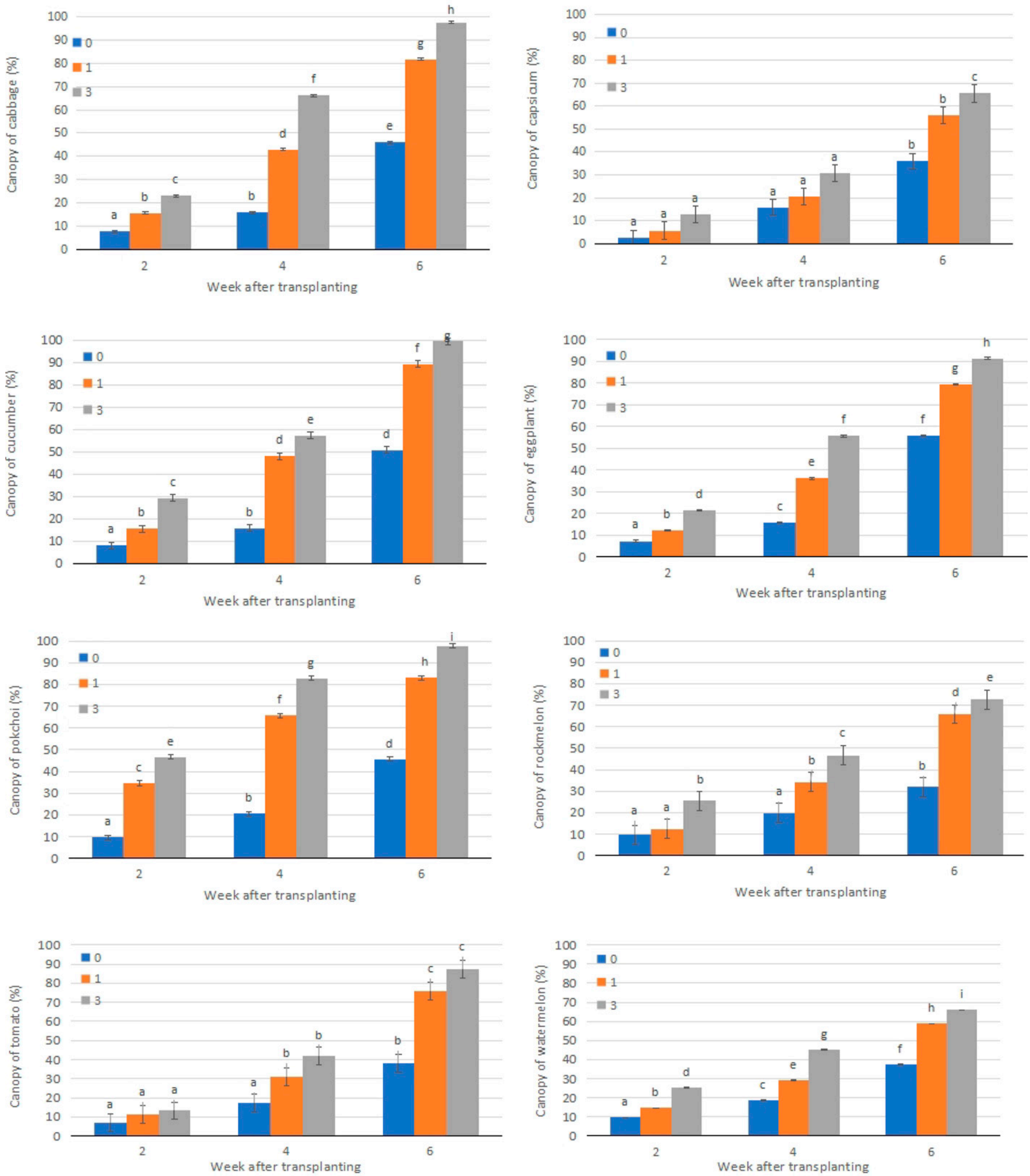

Fig. 4. Response of canopy cover (%) to fortified biochar (FB) rate at weeks 2, 4, and 6 for all tested vegetable species after transplanting. Bleu boxes are the control, orange boxes are fortified biochar 1 t·ha^{-1} with 2% nitrogen (N) and 1% phosphorus (P), and silver boxes are fortified biochar 3 t·ha^{-1} with 2% N and 1% P.

yields of other species, such as cucumber, cabbage, pokchoi, and tomato, increased by four times and that of eggplant increased by five times compared with that of the control treatments. For capsicum, only the higher rate of application (3 t·ha^{-1}) significantly increased yield above the control (Table 7).

Fortified biochar application and vegetable yield interactions. It was hypothesized that crops with a longer crop duration and a larger early canopy cover would respond to a greater extent to fortified biochar application than crops with a short duration and a lower canopy cover (Table 8). In addition, it was hypothesized that vegetables harvested as a whole plant, such as cabbage and pokchoi, would also respond to fortified biochar significantly and to a larger extent compared with those crops for which only fruit was harvested, such as tomato, capsicum, eggplant, rockmelon, and watermelon.

Table 5. Crop duration of tested vegetable species.

Vegetable species	Time to first harvest (d)
Cabbage	95
Capsicum	95
Cucumber	60
Eggplant	75
Pokchoi	45
Rockmelon	70
Tomato	75
Watermelon	70

The model tested in this study to determine the relationship between fortified biochar applications and vegetable yields included the following:

$$Yield = Constant + a * crop\ duration + b * Fortified\ biochar\ application\ rate + c * canopy\ cover\ of\ nil\ at\ two\ weeks\ after\ planting + vegetative\ or\ reproductive.$$

The multilinear regression explained 72% of the variation in yield across the 24 treatments. Each regression factor was significant in the final multiple linear regression (Table 8).

The regression estimates indicated the following equation would predict yield:

$$Yield(t{\cdot}ha^{-1}) = Constant\ of\ -101.4 + 0.86 * Duration\ (days) + 8.8 * Fortified\ Biochar\ rate\ (t{\cdot}ha^{-1}) + 6.7 * Canopy\ cover\ of\ nil\ biochar\ application\ (\%) + 17.7\ if\ Vegetative\ crop.$$

The observed yield and expected yield are shown in Fig. 5. The regression explains the factors that resulted in different yields in this trial. Specifically, fortified biochar rate, the vegetative or reproductive plant parts comprising the harvest, canopy cover at 2 weeks, and overall crop durations explained the observed yield effects of fortified biochar.

Soil

Soil pH and soil respiration. The results of the ANOVA indicated that soil pH was significantly ($P < 0.001$) affected by applying fortified biochar treatments. In addition, the ANOVA indicated that soil pH demonstrated a linear and quadratic response to fortified biochar treatments (Table 9). The lowest soil pH value was found in the control treatment, (pH 6.4), and it increased to 6.5 with the application of fortified biochar 1 t·ha^{-1} and to 6.6 with the application of fortified biochar 3 t·ha^{-1}. In contrast, a significant effect of fortified biochar level treatments on vegetable species and soil respiration was not detected ($P < 0.05$) (Table 9).

Soil nutrients. The results of the ANOVA of the C percentage, N percentage, and extractable levels of soil nutrients using Mehlich 3 extract indicated that all application levels of fortified biochar did not significantly ($P < 0.001$) affect soil nutrients, with the exception of extractable levels of boron (B) and P (Table 10).

Without the soil amendment, the B level was 1.25 mg·kg^{-1}. In the presence of fortified biochar 1 t·ha^{-1}, the B level was increased to 1.6 mg·kg^{-1}. With the application of fortified biochar 3 t·ha^{-1}, the B level was increased to 1.9 mg·kg^{-1} compared with control plots. In addition, the P level without the soil amendment was 12.5 mg·kg^{-1}. With the addition of fortified biochar 1 t·ha^{-1}, the P level was increased to 16 mg kg^{-1}. With the addition of fortified biochar 3 t·ha^{-1}, the P level was increased to more than double that of the control treatments.

The Mehlich 3 extractions indicated that B, P, and Zn levels in the control treatments were low according to the critical level reported by Haefele et al. (2024). However, fortified biochar 3 t·ha^{-1} significantly increased the P and B levels from low to medium (14 mg·kg^{-1} to 30 mg·kg^{-1} and 1.2 mg·kg^{-1} to 1.9 mg·kg^{-1}, respectively). The macronutrient K level was sufficient in the control soil (Table 10).

Impact of fortified biochar application on vegetable economics and profitability

Impact on unsaleable and saleable vegetable yield. After cleaning, sorting, and grading the vegetable yields, the highest unsaleable yield occurred in the control treatments (Table 11). At the farm gate, buyers rejected approximately 50% of the vegetable yields obtained from control plots because those yields did not meet the market's requirements of size, shape, and color. The proportion of unsaleable yields was reduced, and quality increased as the rates of fortified biochar application increased. An increased fortified biochar application resulted in yield that met the more uniform requirements of the market. The highest saleable yield occurred in the fortified biochar 3 t·ha^{-1}, followed by fortified biochar 1 t·ha^{-1} (Table 11), for all vegetables.

Impact of fortified biochar on partial budgets. Overall, the results of partial budgets indicated that the application of fortified biochar 1 t·ha^{-1} significantly increased yield income ($·ha^{-1}) compared with that of the control (Table 12). As the rate of fortified biochar was increased to 3 t·ha^{-1}, the yield ($·ha^{-1}) doubled compared with that of the control. The highest yield increase ($·ha^{-1}) was observed in the cucumber and rockmelon crops. Capsicum produced the lowest $·ha^{-1} yield increase and was the least responsive to fortified biochar treatments.

A comparison of the lower and higher levels of fortified biochar treatment indicated results consistent with the law diminishing returns (Table 12). Specifically, the highest value of dollar return per dollar spent ($sales/$fortified biochar spent) of kilograms of produce per kilogram of fortified biochar (kg yield produced/kg fortified biochar) and of production per kilogram of fortified biochar ($value production/kg fortified biochar used) were obtained with the application of fortified biochar 1 t·ha^{-1} compared with the application of fortified biochar 3 t·ha^{-1} for all species (Table 12).

Impact on gross margin. The highest gross margin was obtained with the cucumber crop (US $54,511 t·ha^{-1}), followed by rockmelon (US $35,424 t·ha^{-1}) (Table 13). The third highest gross margin was occupied by capsicum, pokchoi, and watermelon (average US $22,739 t·ha^{-1}). The gross margins of cabbage, eggplant, and tomato were less than US $17,643 t·ha^{-1}.

The lowest average return on labor was obtained in the control treatments by US $26 ha^{-1}·day^{-1} (Table 13). Fortified biochar 1 t·ha^{-1} significantly increased the return of labor by US $41.4 ha^{-1}·day^{-1}. Fortified biochar 3 t·ha^{-1} significantly increased the return of labor by US $57 ha^{-1}·day^{-1}.

The highest return on labor was obtained with cucumber (US $109 ha^{-1}·day^{-1}), followed by rockmelon (US $93 ha^{-1}·day^{-1}) (Table 13). The third highest return on labor was obtained with capsicum and watermelon (average US $63 ha^{-1}·day^{-1}). The return on labor for cabbage, eggplant, pokchoi, and tomato was less than US $40 ha^{-1}·day^{-1}).

The lowest cost of production for vegetable crops was obtained with the fortified biochar treatment compared with control treatments. The highest cost production was obtained with capsicum (US $5 kg^{-1}) from the control treatment and from the fortified biochar treatment (US $3 kg^{-1}) (Table 13).

Discussion

Response of high-value vegetable crops to fortified biochar

This study built on previous studies in Timor-Leste that investigated the potential

Table 6. *F* value from the analysis of variance (ANOVA) of the effect of fortified biochar rate on yield of each vegetable species.

Source of variation	*df*	Cabbage	Capsicum	Cucumber	Eggplant	Pokchoi	Rockmelon	Tomato	Watermelon
Rep stratum	3	0.4	2.8	0.4	1.7	1.0	0.8	1.3	0.9
Fortified biochar rate	2	1127***	26.4***	4958***	9173***	40.0***	2285***	138***	552***
Linear response to fortified biochar rate	1	2107***	52.5***	9793***	18325***	79.9***	4473***	276***	1022***
Quadratic response to fortified biochar rate	1	147***	0.8	123.4***	20.1**	4.0	96.4***	0.4	83***
Residual	6								
CV (%)		2.5	21.6	1.7	1.6	18.5	2.6	11.1	3.4

Refer to mean values presented in Table 7. * $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$.
df = degrees of freedom.

Table 7. Response of vegetable yield (t·ha^{-1}) to fortified biochar application.

	Yield (t·ha^{-1}) from fortified biochar rate treatments			
Vegetable species	0 (Control)	1 t·ha^{-1}	3 t·ha^{-1}	*CV* %
Cabbage	36.3 a	66.1 b	89.6 c	2.5
Capsicum	1.9 a	3.0 a	5.7 b	21.6
Cucumber	15.1 a	33.0 b	56.5 c	1.7
Eggplant	6.0 a	13.8 b	31.6 c	1.6
Pokchoi	9.6 a	25.1 b	39.1 c	18.5
Rockmelon	14.9 a	21.5 b	48.4 c	2.6
Tomato	8.4 a	18.2 b	34.9 c	11.1
Watermelon	11.3 a	20.2 b	26.8 c	3.4

Mean yields with similar letter(s) are statistically similar, and those with dissimilar letter(s) differ significantly. Letters refer to within-row differences for each species only.

Table 8. Estimated parameters of multilinear regression explaining the interaction of fortified biochar on vegetable yield across eight species.

Parameter	Estimate	*SE*	*P*
Constant	−101.4	23.9	<0.001
Fortified biochar rate	8.8	1.9	<0.001
Vegetative or reproductive	17.8	5.7	0.006
Canopy cover at 2 weeks from control	6.7	1.5	<0.001
Duration	0.86	0.2	<0.001

SE = standard error.

for maximizing crop yield using biochar and fortified biochar under much higher rates of biochar and fortified biochar. Our study focused on relatively low rates of biochar and fortification that are most likely to be available and affordable for smallholder farmers in the same context because maximizing yield may not be their main consideration.

Overall, the findings of this study are consistent with those of other studies that demonstrated that fortified biochar is effective for improving crop yields (Bai et al. 2022; Ndoung et al. 2021). Furthermore, in Timor-Leste, very large increases in yield occurred relative to a nationally low baseline in the context of low inputs and low yields (Williams et al. 2023). The yields in this study are also very high compared with national production (Ministry of Agriculture and Fisheries 2021) and UNTL research findings (Gomes et al. 2023; Gusmao et al. 2023) in Timor-Leste. In fact, even the relatively low input of 1 t·ha^{-1} resulted in significant economic benefit (cost of production) to household economy in this setting. Importantly, this study also demonstrated that the quality (saleability) of the yield also increased substantially under fortified biochar treatment for all vegetable species.

Biochar alone can act as a fertilizer. However, fortified biochar, if inputs are available and affordable, may be a better option. In this study, application of fortified biochar 3 t·ha^{-1} significantly increased vegetable yields by 258% compared with UNTL unfortified biochar trialed at 181% (Gomes et al. 2023). The application of fortified biochar 3 t·ha^{-1} produced the highest yields of cabbage, capsicum, cucumber, eggplant, pokchoi, rockmelon, tomato, and watermelon (89.6, 5.7, 56.5, 31.6, 39, 48, 35, 27 t·ha^{-1}, respectively). The yields of cabbage, capsicum, cucumber, eggplant, tomato, and watermelon at the national level are only 11.5, 3, 8.5, 4, 5, and 6 t·ha^{-1}, respectively (Al Hasan et al. 2022; Ministry of Agriculture and Fisheries 2021), and that of rockmelon is 24 t·ha^{-1} (Gomes et al. 2023). National yield data of pokchoi were not available for comparison.

The response to fortified biochar application has been seen in both the vegetative and reproductive stages of growth and yield. Higher yields could be expected with higher rates of fortified biochar application through greater light interception by increased canopy or height. Two weeks after transplanting, many vegetable species were significantly taller and had a higher canopy cover with fortified biochar 3 t·ha^{-1}. This is consistent with most crops such as capsicum, pokchoi, and tomato, which have a strong linear response to the application rates. Higher yields are likely to be achieved with higher rates of application.

The improvement of high-value vegetable yields was partially achieved in this study because the application of fortified biochar significantly increased soil pH compared with control treatments. This finding is consistent with the results of a previous meta-analysis (Bai et al. 2022) that also demonstrated that biochar-based fertilizer significantly increased soil pH, which positively influenced soil nutrient availability for vegetable growth. Similarly, in this study, the presence of fortified biochar significantly increased plant nutrients such as B and P availability in the soil of vegetable crops in the dry season. Because B is a micronutrient that plays an important role in a diverse range of plant functions, including cell wall formation and stability, maintenance of structural and functional integrity of biological membranes, and movement of sugar or energy into the growing part of plants (Cakmak and Römheld 1997), its deficiency in soil may impact vegetable growth, as identified in the soil of control treatments. Consequently, B in the leaf tissue cannot be transported sufficiently into the reproductive organs during plant growth (Brown et al. 2002). However, applying fortified biochar significantly increased B levels in the soil and increased vegetable yields compared with control treatments. Many studies also reported that adequate B in the soil improves root uptake of P to support plant growth and yield (Brown et al. 2002; Cakmak and Römheld 1997).

Abobatta and Abd Alla (2023) revealed that, in the arid and semi-arid regions, different vegetable crops such as potatoes, tomatoes, cucumber, pepper, and eggplant suffer from P deficiency, which inhibits the vegetative stage, reduces the productivity of various crops, and delays fruit ripening. However, applying biochar-based fertilizer increases P availability, which is a pivotal nutrient for achieving a maximum yield of vegetables and fruits (Cox et al. 2012). An increase in the P concentration at the beginning of the

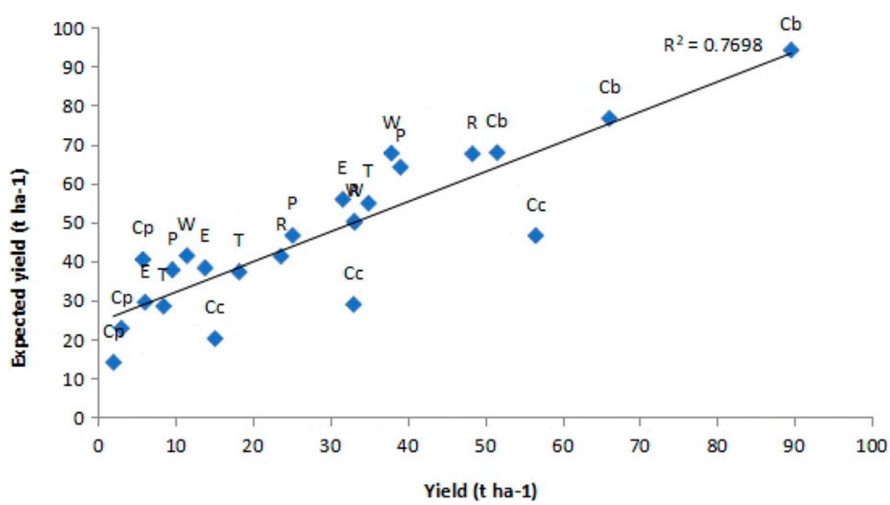

Fig. 5. Yields (t·ha^{-1}) of eight species with three application rates of fortified biochar (0, 1, and 3 t·ha^{-1}) and expected yields from multiple liner regression. Inputs for the multiple linear regression were canopy cover of that species on no fortified biochar treatment at 2 weeks after planting, rate of application of fortified biochar, and crop duration. Vegetable codes are as follows: Cb = cabbage; Cc = cucumber; Cp = capsicum; E = eggplant; P = pokchoi; R = rockmelon; T = tomato; W = watermelon.

Table 9. *F* values from the analysis of variance (ANOVA) of soil pH and soil respiration.

Source of variation	*df*	pH	Soil respiration (mg/kg C-CO_2/day)
Fortified biochar rate	2	55.4***	0.1
Linear response to fortified biochar rate	1	92.7***	0.2
Quadratic response to fortified biochar rate	1	18***	0.03
Species fortified biochar rate	2	0.4	2.7
Species linear response to fortified biochar rate	1	0.1	5.3
Quadratic response to fortified biochar rate	1	0.7	0.02
Residual	15		
CV (%)		0.6	20.3

Refer to mean values presented in Table 10. * $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$.

Table 10. Soil element comparison with critical levels, mean levels under treatments, *P* values, and *CV* % for fortified biochar rate application. *F* values from the analysis of variance (ANOVA) of soil nutrients with fortified biochar rates for all vegetable species.

Soil elements	Comparison with levels of low, medium, or high (mg/kg)	Control (mg/kg)	1 $t{\cdot}ha^{-1}$ (mg/kg)	3 $t{\cdot}ha^{-1}$ (mg/kg)	*F* prob respond to biochar rate	*F* prob of linear respond to biochar rate	*CV* %
Calcium	High (600–900)	3701	3662	3580	0.9	1.5	6.8
Boron	Low (1.0–1.5)	1.25 (a)	1.61 (b)	1.93 (b)	0.1	4.7**	16.0
Copper	Medium (1.0–20)	3.8	3.7	3.9	0.1	0.3	10.8
Iron	Medium (80–300)	168	168	169	1.3	0.1	20.0
Potassium	Medium (191–600)	228	244	207	1.7	1.7	16.7
Magnesium	High (72–148)	549	566	533	1.2	0.9	8.4
Manganese	High (300–500)	465	375	334	0.03	0.8	9.6
Phosphorus	Low (5–15)	14.6 (a)	17.0 (b)	30.1 (c)	0.2	5.0***	70.4
Sulfur	High (41–50)	58.8	54.2	55.8	0.3	0.3	30.1
Zinc	Low (1.0–10)	4.29	4.36	4.42	0.1	0.01	35.0
Total N %	Medium (0.15–0.25)	0.205	0.206	0.206	0.02	0.05	14.0
Total C %	Low (2–4)	2.30	2.45	2.56	0.05	0.05	43.5

Asterisks indicate * $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$. Comparison levels are from Haefele et al. (2024).
C = carbon; N = nitrogen.

growing season resulted in a significant increase in plant height and canopy morphological growth, as found in this study (Abbasian et al. 2018).

Impact of fortified biochar on soil nutrients

The results of the soil study indicated that the soil at this study site was lacking in P, Zn, and B. This finding is similar to those of previous studies conducted by Williams et al. (2023) and Howeler et al. (2002). These nutrient deficiencies may occur because of the long-term rice monoculture system, which causes excessive soil nutrient mining of P, Zn, and B, as reported by (Williams et al. 2023). In contrast, the contents of Ca and Mg are high compared with the critical point reported by Haefele et al. (2024). The high content of Ca may be tightly bound with P and may result in P unavailability for plant growth (Shrestha et al. 2020).

In contrast, the Mg level is very high and may hamper phosphate transfer in the soil and plant (Shrestha et al. 2020). In addition, the manganese (Mn) and S levels are also high in the soil and may become toxic to plants (Mahmud et al. 2021). However, in this study, these soil elements did not become toxic to vegetable growth because the yield of vegetables amended with fortified biochar was significantly higher than that obtained from control treatments. This evidence indicated that soil elements such as Ca, Mg, Mn, and S are not becoming limiting factors for vegetable production compared with macronutrient elements such as N, P, and K (Shrestha et al. 2020).

In this study, adding fortified biochar increased soil pH in the experiment site. As the rates of fortified biochar increased, soil pH also increased, similar to other studies (Hass et al. 2012). Increasing soil pH promotes nutrient availability and supports plant growth and yield (Zhang et al. 2023).

In addition, applying fortified biochar significantly increased the P level in the soil (Williams et al. 2023), suggesting that the yield response to soil in Maliana paddy field areas treated with fortified biochar is also attributable to P and B availability. After being amended with fortified biochar, the concentrations of P and B achieved medium critical values of 16 to 30 $mg{\cdot}kg^{-1}$ and 1.5 to 20 $mg{\cdot}kg^{-1}$, respectively (Haefele et al. 2024). In this study, we believe that the extra soil available P and B likely were supplied from the SP36, but not the biochar.

However, the application of fortified biochar did not significantly affect soil respiration following its application. This may be attributable to the relatively meager biochar application rates in this study compared with high rates of biochar application in other studies in which an effect has been detected. Meta-analyses (Sagrilo et al. 2015; Stewart et al. 2013) indicated that the high soil respiration (CO_2 effluxes) was associated with high biochar application rates of more than 40 $t{\cdot}ha^{-1}$. The use of biochar at very high dosages is impractical for low biomass of rice husks available in Timor-Leste, which already constrain farmers' adoption of biochar directly in their vegetable production (da Costa Guterres et al. 2019).

If farmers continuously use low rates of fortified biochar for vegetable production in paddy field areas after the harvest of rice, then it may induce growth of the microbial community (Knoblauch et al. 2021; Tasneem

Table 11. Unsaleable and saleable yield after sorting and grading the vegetables. The causes of unsaleable yield were wilting for cabbage and pokchoi and size, shape, or color that did not meet market requirements for other species.

	Fortified biochar rate ($t{\cdot}ha^{-1}$)								
	0			1			3		
Vegetable species	Saleable ($t{\cdot}ha^{-1}$)	Unsaleable ($t{\cdot}ha^{-1}$)	Unsaleable (%)	Saleable ($t{\cdot}ha^{-1}$)	Unsaleable ($t{\cdot}ha^{-1}$)	Unsaleable (%)	Saleable ($t{\cdot}ha^{-1}$)	Unsaleable ($t{\cdot}ha^{-1}$)	Unsaleable (%)
Cabbage	15.7	20.6	56.7	54.3	11.8	17.9	73.6	16.0	17.9
Capsicum	1	0.9	47.4	2.9	0.1	3.3	5	0.7	12.3
Cucumber	9.6	5.5	36.4	32	1	3.0	56.5	0	0
Eggplant	2.6	3.4	35.4	13	0.8	5.8	30.1	1.5	4.7
Pokchoi	5.4	4.2	43.8	14.6	10.5	41.8	24.5	14.6	37.3
Rockmelon	7.9	7	47.0	20.1	1.4	6.5	42.8	5.6	11.6
Tomato	3.2	5.2	61.9	18	0.2	1.1	34	0.9	2.6
Watermelon	5.2	6.1	54.0	20	0.2	1.0	26	0.8	3.0

Table 12. Partial budget at the farm gate of vegetable species at different levels of fortified biochar rate (t·ha^{-1}) application.

Vegetable species	Fortified biochar rate (t)	Saleable yield (t·ha^{-1})	Cost of fortified biochar ($·kg^{-1})	Price of vegetable ($·kg^{-1})	Increase yield (t·ha^{-1})	Value ($·ha^{-1})	Increased value ($·ha^{-1})	Cost of fortified biochar ($·ha^{-1})	Value of product per cost of fortified biochar ($·$$^{-1}$)	Increased yield per kg of fortified biochar (kg·kg^{-1})	Increased value per fortified biochar ($·kg^{-1})
Cabbage	0	15.7	0.35	0.5	0	7850					
Cabbage	1	54.3	0.35	0.5	38.6	27,150	19,300	350	55.1	38.6	19.3
Cabbage	3	73.6	0.35	0.5	57.9	36,800	28,950	1050	27.6	19.3	9.6
Capsicum	0	1.0	0.35	2	0	2000					
Capsicum	1	2.9	0.35	2	1.9	5800	3800	350	10.9	1.9	3.8
Capsicum	3	5.0	0.35	2	4.0	10,000	8000	1050	7.62	1.3	2.7
Cucumber	0	9.6	0.35	1	0	9600					
Cucumber	1	32.0	0.35	1	22.4	32,000	22,400	350	64.0	22.4	22.4
Cucumber	3	56.5	0.35	1	46.9	56,500	46,900	1050	44.7	15.6	15.6
Eggplant	0	2.3	0.35	0.75	0	1725					
Eggplant	1	13.0	0.35	0.75	10.7	9750	8025	350	22.9	10.7	8.0
Eggplant	3	30.1	0.35	0.75	27.8	22,575	20,850	1050	19.8	9.3	6.9
Pokchoi	0	5.4	0.35	0.8	0	4320					
Pokchoi	1	14.6	0.35	0.8	9.2	11,680	7360	350	21.0	9.2	7.4
Pokchoi	3	24.5	0.35	0.8	19.1	19,600	15,280	1050	14.5	6.4	5.1
Rockmelon	0	7.9	0.35	1	0	7900					
Rockmelon	1	20.1	0.35	1	12.2	20,100	12,200	350	34.9	12.2	12.2
Rockmelon	3	42.8	0.35	1	34.9	42,800	34,900	1050	33.2	11.6	11.6
Tomato	0	3.2	0.35	0.75	0	2400					
Tomato	1	18.0	0.35	0.75	14.8	13,500	11,100	350	31.7	14.8	11.1
Tomato	3	34.0	0.35	0.75	30.8	25,500	23,100	1050	22.0	10.3	7.7
Watermelon	0	5.2	0.35	1	0	5200					
Watermelon	1	20.0	0.35	1	14.8	20,000	14,800	350	42.29	14.8	14.8
Watermelon	3	26.0	0.35	1	20.8	26,000	20,800	1050	19.8	6.9	6.9

and Zahir 2017). However, because this study was performed over only 1 year, insufficient data about the long-term persistence of fortified biochar amendment impacts on soil respiration were obtained.

Impact of fortified biochar on the profitability of each vegetable species

The partial budget analysis in this study indicated that fortified biochar 3 t·ha^{-1} was economically better than fortified biochar 1 t·ha^{-1} and control because the higher rate increases the yields and gross margin of growing these vegetables. An increase in vegetable yields is worth the investment of adding higher amounts of fortified biochar.

The innovation of fortified biochar is feasible for smallholder farmers to adopt because they only grow vegetables on one-tenth of a hectare of their land. For this area of cultivation, it is affordable for farmers to use fortified biochar 3 t·ha^{-1} to obtain the highest economic return compared with fortified biochar 1 t·ha^{-1} and control treatments. However, even the application of fortified biochar at 1 t·ha^{-1} increased the economic benefit of cropping.

Applying fortified biochar to vegetable crops reduced unsaleable yields and increased saleable yields because of the improved quality, size, shape, and color. These improvements resulted in more of the crop meeting the quality standards required by supermarket and mass markets. The application of fortified biochar 1 t·ha^{-1} and 3 t·ha^{-1} increased the gross margins by 99% and 249%, respectively, compared with the traditional method of no soil treatment. The highest gross margin of vegetable species was obtained with cucumber, pokchoi, rockmelon, and watermelon. These four vegetable species showed more profitability regarding net returns per dollar investments. These four species are also harvested quickly and can be grown at different times of the dry season, resulting in a steadier income.

In addition, these four vegetable species generate employment opportunities for an average of 493 d, with an average return of labor of US $75.7 ha^{-1}·day^{-1}. The other four species, cabbage, capsicum, eggplant, and tomato, generate employment opportunities for an average of 501 d, with an average return of labor US $37.9 ha^{-1}·day^{-1}. The average total days allocated for cabbage, capsicum, eggplant, and tomato were longer because these species are long-duration crops that need more than 75 d to harvest. Capsicum had the highest cost of production (US $3·kg^{-1}). This high cost of production occurred because capsicum seeds were purchased from Australia and had a high shifting cost, and because it is a long-duration crop (95 d), which impacted the additional costs of irrigation, weeding, pest control, and disease control.

The gross margin analysis indicated that the overall labor return obtained in this study was very high compared with the government labor payment rate of US $3.00·d^{-1}. The high labor wage obtained from cucumber, pokchoi, rockmelon, and watermelon is considered a positive innovation that promotes

Table 13. Gross margin of vegetable species at different levels of fortified biochar ($t \cdot ha^{-1}$) application.

Treatment	Fortified biochar rate ($t \cdot ha^{-1}$)	Yield ($t \cdot ha^{-1}$)	Total variable cost ($\$ \cdot ha^{-1}$)	Gross return ($\$ \cdot ha^{-1}$)	Gross margin ($\$ \cdot ha^{-1}$)	Labor (d)	Return on labor ($\$ \cdot ha^{-1} \cdot day^{-1}$)	Gross margin including labor ($\$ \cdot ha^{-1}$)	Cost of production ($\$ \cdot kg^{-1}$)
Cabbage	0	15.7	322	7450	7128	378	18.84	5,237	0.33
Cabbage	1	54.3	922	13,575	12,653	471	26.86	10,298	0.19
Cabbage	3	73.6	1989	18,400	16,411	545	30.13	13,688	0.19
Capsicum	0	1.0	397	7600	7203	303	23.75	5,688	5.69
Capsicum	1	2.9	997	12,000	11,003	325	33.86	9,378	3.23
Capsicum	3	5.0	2064	22,800	20,736	367	56.50	18,901	3.78
Cucumber	0	9.6	322	15,100	14,778	297	50.00	13,293	1.38
Cucumber	1	32.0	922	33,000	32,078	386	83.05	30,148	0.94
Cucumber	3	56.5	1989	56,500	54,511	500	109.03	52,012	0.92
Eggplant	0	2.3	322	3375	3053	337	9.06	1,368	0.59
Eggplant	1	13.0	922	7481	6559	431	15.21	4,403	0.34
Eggplant	3	30.1	1989	17,494	15,505	675	22.98	12,132	0.40
Pokchoi	0	5.4	322	6016	5694	315	18.06	4,117	0.43
Pokchoi	1	14.6	922	16,192	15,270	534	28.58	12,598	0.49
Pokchoi	3	24.5	1989	26,688	24,699	759	32.54	20,904	0.50
Rockmelon	0	7.9	1649	12,600	10,951	275	39.8	9,576	1.21
Rockmelon	1	20.1	2209	20,400	18,191	309	58.79	16,644	0.83
Rockmelon	3	42.8	3276	38,700	35,424	379	93.36	33,527	0.78
Tomato	0	3.2	322	4725	4403	286	15.42	2,976	0.93
Tomato	1	18.0	922	10,237	9316	337	27.61	7,628	0.42
Tomato	3	34.0	1989	19,631	17,643	420	42.01	15,543	0.46
Watermelon	0	5.2	1649	11,200	9551	270	35.35	8,200	1.58
Watermelon	1	20.0	2249	20,000	17,751	308	57.63	16,211	0.81
Watermelon	3	26.0	3316	26,100	22,784	335	67.94	21,108	0.81

household income in the dry season and reinvestment for subsequent rice in the wet season (TOMAK 2016). The high labor wage also may allow farmers to attract labor. Increasing the returns to labor will help prevent young farmers from moving to cities to find alternative jobs with higher salaries. This mechanism may overcome labor shortage problems, thereby enhancing agriculture's overall contribution to economic growth in rural areas (Prasad 2016).

Farmers explained that household members consume unsaleable fruits and vegetables daily. Consuming these unsaleable fruit and vegetable yields may reduce malnutrition in farm households (Farmery et al. 2020). In addition, farmers use vegetable waste, particularly cabbage and pokchoi, to feed pigs. Pigs play an important cultural and financial role in farmers' households (Hunter et al. 2022). Therefore, using waste products from cabbage and pokchoi may increase pig production, resulting in the sale of these pigs to make money to cover family expenses, including agricultural inputs for subsequent rice production in the wet season.

Conclusion

Applying fortified biochar increased yields of high-value vegetable crops and economic and noneconomic benefits to smallholder farmers in Timor-Leste. Regarding fortified biochar rates, the application of 3 $t \cdot ha^{-1}$ is economically high based on the gross margin analysis. Increased margins of 122% obtained through fortified biochar 1 $t \cdot ha^{-1}$ and 208% through fortified biochar 3 $t \cdot ha^{-1}$, as found in this study, would significantly improve the socio-economic status of smallholder rice farmers. This new income generation will increase farmers' ability to reinvest in rice production in the subsequent wet season.

Based on the findings of this study, farmers can consider adopting the use of fortified biochar. Fortified biochar at 3 $t \cdot ha^{-1}$ (N 60 $kg \cdot ha^{-1}$ and P 30 $kg \cdot ha^{-1}$) and even 1 $t \cdot ha^{-1}$ are likely to be affordable for many smallholder farmers who typically cultivate vegetables over only one-tenth of a hectare of paddy field.

However, the decision-makers must ensure that policy and regulation mechanisms for biochar production, distribution, and utilization meet farmers' objectives of increasing soil fertility, vegetable production, and income generation. In addition, the government should explore new policy mechanisms that boost access to agricultural inputs such as high-value vegetable seeds, urea, and SP-36. These policy mechanisms and their recommendations will ensure farmers' access to the inputs to uptake innovations such as low-dose fortified biochar in their vegetable production in a vegetable–rice cropping sequence in paddy field areas of Timor-Leste. The extra income generated by vegetable income may be used by farmers to cover the costs of wet season rice cropping and address the national problem of decreasing rice production.

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