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Effect of the Interaction between Wood Vinegar and Biochar Feedstock on Tomato Plants

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Abstract

This study investigated the effect of the interaction between wood vinegar and biochar feedstock on total biomass, fruit weight (yield), and sugar content of tomato plants (*Solanum lycopersicum* L.). An experiment was conducted in two locations with six different biochar types produced from either plant or animal feedstock. Each biochar was incorporated into soil (1:2500 g/g) along with chemical fertilizer. Wood vinegar was diluted with water (1:200 mL) and applied once weekly for the vinegar treatment. Biochar application resulted in a higher yield and biomass of the chicken manure biochar owing to its high ammonium-nitrogen content. Vinegar application increased the yields of the plant feedstock, which was particularly evident for most of the yield parameters with the bamboo biochar. Regardless of treatment, yield and biomass were not significantly different between the animal and plant feedstock. The sugar content was higher for the chicken manure and animal litter biochar, which was attributed to better pH conditions. The combination of plant feedstock biochar and vinegar application for improving the yield of tomatoes is promising. In contrast, vinegar application could potentially limit the yield and fruit sugar content of tomato plants treated with animal feedstock biochar.

Highlights

- The soil was amended with biochar, with or without vinegar application.
- The chicken manure biochar plants had the highest yield and biomass.
- Vinegar application increased the yield of the plant feedstock.
- Plant and animal feedstock plants had similar yield and biomass.
- The pH of the animal feedstock was better because of higher CO_2 and MgO contents.
- Fruit sugar content for animal feedstock plants was better due to higher phosphorus.

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1 Introduction

The impact of climate change on food security, primarily in developing countries, cannot be overemphasized. Owing to soil degradation, drought and high depletion of soil mineral nutrients are common in many countries in Asia, South America, and sub-Saharan Africa (Guerra et al. 2020). Biochar is considered helpful as a soil amendment under the Climate-Smart Agriculture (CSA) approach for resilient agriculture because of its rich organic carbon sequestration (Lehmann et al. 2015). Ndede et al. (2022) demonstrated that biochar mitigates drought in sandy agricultural soils by improving their hydrological properties. Biochar use in CSA is promoted by the Food and Agricultural Organization of the United Nations (Palombi and Sessa 2013; Lipper et al.

2014). Biochar has been recognized for its carbon capture and storage in the special report of the Intergovernmental Panel on Climate Change (IPCC) (Schmidt et al. 2018). Recently, several studies have reported biochar as a soil enhancer for improving crop yield due to its ability to retain moisture and improve water-holding capacity for drought-resilient agriculture (Blanco-Canqui 2017; Kassaye et al. 2021; Martinsen et al. 2015). Similarly, biochar enhances soil fertility because of the *in situ* soluble, organically bound nutrients (Abbaszadeh-Dahaji et al. 2019; Karimi et al. 2020). Reports indicate that increased application of biochar in the root zone of soil deficient in phosphorus increases plant-available phosphorus concentration, increasing plant growth and phosphorus uptake by 59% and 73%, respectively (Meyer 2022). Biochar influences phosphorus mineralization and phosphatase enzyme activity, which is responsible for converting organic phosphorus into inorganic forms for uptake (Viraj et al. 2019). Nutrients are labile and supplied through mineralization over time (Kammann et al. 2015; Nele et al. 2018; Schmidt et al. 2015). This phenomenon can be dependent on feedstock material, as demonstrated by the slow release of either augmented micronutrients or NPK fertilizer with biochar for plant uptake (Das et al. 2021a, b).

The primary abiotic factor affecting tomatoes is drought, contributing to an approximate 70% reduction in yield (Ibrahim et al. 2020; Oscar 2018). Akhtar et al. (2014) and Petruccelli et al. (2015) reported that soil formulated with biochar improved tomato yield without affecting fruit sweetness, while decreasing chlorophyll, a feature for photosynthesis. Conversely, Vaccari et al. (2015) found that biochar did not increase tomato yield; instead, it increased the ammonium, phosphorus, and potassium availability. Using biochar for improving crop production without supplying the required nitrogen and other essential nutrients is not expected to increase yield (Filiberto et al. 2013; Ye et al. 2020). However, this improvement may vary depending on the feedstock (plant or animal) or biochar type.

Janu et al. (2021) and others have characterized biochar by particle size, feedstock, ash content, and specific surface area to improve its nutrient availability and pH level (Dhar et al. 2020; Pradhan et al. 2020; Prasad et al. 2020). However, the pH of soil formulated with biochar is of concern. Nutrients such as phosphorus depend on pH (Brod 2015; Lindsay 1979), and phosphorus is responsible for sugar phosphate synthesis in tomato fruits (Kanayama 2017). Moreover, vinegar, a liquid by-product of condensed vapor generated during biochar pyrolysis, has been reported to enhance yield by improving nutrient uptake (Lei et al. 2018; Pan et al. 2017). However, vinegar is acidic with a pH of 2.5–3.0, decreasing the growth medium pH and hindering phosphorus bioavailability (Travero and Mihara 2015; Yatagai et al. 2002). Applying an appropriate concentration

of wood vinegar can be beneficial for crop production (Luo et al. 2019; Zhu et al. 2021) owing to the presence of various functional organic substances, including organic acids, ketones, aldehydes, alcohols, benzene and its derivatives, heterocyclic compounds, phenols and their derivatives, alkyl phenyl ethers, carbohydrate derivatives, and nitrogen compounds, in beneficial proportions (Lu et al. 2019; Ma et al. 2013). However, there is limited information on the application of both biochar and wood vinegar to improve the yield and sugar content of tomatoes, with a few studies focusing on the effect of wood vinegar on growth parameters of other crops (Lei et al. 2018; Pan et al. 2017). Therefore, this study investigated whether the interaction between vinegar application and biochar feedstock affects the yield and sugar content of tomatoes and whether different feedstocks influence the effectiveness of wood vinegar in lowering yield. The results will justify whether plant or animal feedstock is more advantageous when used with wood vinegar for the growth and development of tomato plants. The paper proposes that vinegar may be involved in increasing the yield of tomato plants owing to its chemical properties, depending on biochar type. Additionally, the growth medium pH may limit the sugar content of tomato fruit due to the unavailability of phosphorus nutrients. Overall, this study provides a scientific basis for the use of vinegar and biochar for tomato production.

2 Material and Methods

2.1 Plant, Soil, and Biochar Materials

The plant materials used were 24-day-old tomato (cv. *Monotaro*) seedlings, purchased along with the soil material from Japan Agriculture (JA) in Kanazawa. The soil had a total carbon and nitrogen content of 1.14% and 0.13%, respectively (Suppl. Table 4). Details about the soil are available online (https://www.jstage.jst.go.jp/article/dojo/53/1/53_KJ00001687356/_pdf). Soil alone was used as the control.

Biochar was produced by Meiwa Co. Ltd. (Kanazawa, Japan) by pyrolysis using a batch-type kiln carbonizer (ECO200, Kanazawa City, Ishikawa, Meiwa Co. Ltd., Japan; https://www.meiwa-ind.co.jp/en/) with an external heating mechanism for cattle manure, chicken manure, and bamboo, at a carbonization temperature of approximately 400–500 °C for 2 h. A rotary kiln carbonizer (MES50, Kanazawa City, Ishikawa, Meiwa Co. Ltd., Japan) with an internal heating mechanism was used for slaughterhouse wastewater, rice husk, and woodchip carbonization at 400–500 °C for 30 min according to procedures outlined by Ferjani et al. (2019) and Song et al. (2012) (Suppl. Table 5 Additional information). The six different biochar materials were classified into two

feedstock types: plant and animal. Plant feedstocks included bamboo biochar (BB) made from dried bamboo, rice husk biochar (RHB) made from rice husks, and woodchip biochar (WB) made from Japanese cedar trees (*Pinus thunbergiana*). Animal feedstocks included chicken manure biochar (CMB) made from chicken manure, animal litter biochar (ALB) made from cattle manure, and sludge biochar (SB) made from slaughterhouse wastewater.

2.2 Soil and Biochar Chemical Analysis

The textural class of the soil used for potting was loamy soil, as determined at the soil chemistry laboratory of Shimane University. The acidity (pH) of the biochar, soil, and combination growth medium of the biochar and soil together were analyzed using a pH/ion meter F-72 (https://www.horiba.com/int/). Biochar and soil electrical conductivity (EC) were analyzed using the Hanna Gro Line EC Tester (https://hanna.co.jp/). The mineral nutrients analyzed included ammonium-nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N), phosphorus pentoxide (P_2O_5), potassium oxide (K_2O), calcium oxide (CaO), magnesium oxide (MgO), iron (II) ions (Fe^{2+}), and manganese oxide (MnO) (Table 2). Soil and biochar mineral nutrients were analyzed before incorporation using the Doctor Soil test kit (Japan Bio Farm), an extraction method used for soil and ecological farming. This procedure was published by the Japan Soil Association by Daisei GOTO, Agricultural Science Equipment Division, Fujihira Industry Co., Ltd.

2.3 Soil Formulation and Experimental Site

The biochar to soil ratio was 1g/2.5 kg (1:2500 g/g) for all biochar treatments. The biochar mixed with soil was further incorporated with lime (17.07 g pot^{-1}, 80% CaO: 20% MgO) and fertilizer (13.66 g pot^{-1}, N: P: K: Mg: Mn: B at a ratio of 14: 10: 13: 3: 0.4: 0.2, respectively). The experiments were conducted in 2018 at the Meiwa Co. Ltd. experimental site and a farmer's field in Minato-Kanazawa, Japan. Both experiments were conducted in a greenhouse at 36°37′26″ N and 136°37′51″ E.

2.4 Wood Vinegar, Watering, Treatment, and Transplanting

The wood vinegar was produced by Meiwa Co. Ltd. (Kanazawa, Japan). Approximately 3,000 mL of wood vinegar was harvested by condensing the syngas emitted over the 3-hour pyrolysis of 40 kg of pine wood (*Pinus thunbergiana*). The chemical composition of wood vinegar was previously reported by Jindo et al. (2022). Vinegar was diluted with water (1:200 mL) and applied once weekly for fertigation. Irrigation was performed manually once or twice daily to prevent dehydration of growth medium. To study the effect of vinegar application, together with the control soil treatment, each biochar type had two sets of treatments: with and without vinegar. Treatments contained five replicates each. Tomato seedlings were transplanted on April 30, 2018, from a 45 cm × 60 cm spacing (3.7 plants m^{-2}) into an individual pot (area = 0.1138 m^2).

2.5 Parameter Measurements

Yield, yield parameters, and biomass at maturity were estimated, including total fruit weight (yield), total dry weight (biomass), harvest index (yield/biomass), number of fruits per plant (# Fruit plant^{-1}), single fruit weight (SFW), total fruit weight per plant (TFWP), 100 fresh fruit weight (100FFW), and plant height. Plant height was measured using measuring tape two weeks after transplant (2WAT) and four weeks after transplant (4WAT). Leaf chlorophyll (SPAD) in the four most expanded leaves of each plant was measured at 2WAT and 4WAT using a SPAD 502m (Konica Minolta, Inc.). Leaf area index (LAI) was calculated according to the following imaging procedures at 2WAT and 4WAT. Images were captured as described by Nakano et al. (2020). The imaging procedure used an iPhone 7plus digital camera (12 megapixels) and ImageJ software as described by Easlon et al. (2014) and Tanaka et al. (2009). ImageJ software employs threshold-based pixel count measurements (Schneider et al. 2012). Sugar content of the fruit was measured using a Refractometer IPR-2O1α (BRIX-meter) after crushing the ripe fruit using an electric blending machine.

2.6 Definition of the Effectiveness of Vinegar

The effectiveness was defined as the ratios of measurements from those treated with vinegar to those without the vinegar treatment, as follows:

$$\text{Effectiveness} = \text{Vinegar} \frac{\text{application}}{\text{No}} \text{vinegar application}$$

When effectiveness = 1, > 1, or < 1, the effectiveness of vinegar was deemed neutral, positive, or negative, respectively.

2.7 Experimental Design and Statistical Analysis

The experimental design of this study was a randomized complete block. Six different biochar types were designed as three-factorial experiments, comprising two feedstocks (animal feedstock and plant feedstock), two treatments (vinegar and no-vinegar), and two locations. ANOVA and *T*-tests

were conducted using R software (R Core Team 2015), and graphs were created using Microsoft Excel 2017.

3 Results

3.1 pH and EC of the Soil and Biochar

The soil pH (5.42) indicated the soil was acidic and EC value (0.03) indicated low soil salinity (Table 1). The pH and EC values were 8.1 and 0.84 for BB, 7.28 and 0.39 for WB, 5.64 and 0.2 for RHB, 7.39 and 0.48 for SB, 9.56 and >4 for ALB, and 9.41 and >4 for CMB, respectively. In accordance with Brady and Weil (2008), plant feedstock pH values indicate that BB is alkaline, WB is neutral, and RHB is acidic. Overall, EC values of all plant feedstocks indicate low salinity. For the animal feedstocks, pH values indicated ALB and CMB are alkaline, while SB was neutral. The EC values indicated CMB and ALB have

high salinity, while that of SB is low. EC values of animal feedstocks, except SB, were high because their mineral nutrients were high.

3.2 Soil and Biochar Chemical Composition

Soil mineral nutrient analysis indicated poor nutrients content, except for the NO_3-N readily available for plant uptake (2.82 mg·kg^{-1} DW), which was considerably higher ($p=0.000$) than those of the biochar types (Table 2). However, mineral nutrients varied among the different plant feedstock biochar types. According to the soil fertility classification, BB had a medium P_2O_5 level of 1.39 g·kg^{-1} DW (Sanchez et al. 1982). WB had the highest CaO (1.78 g·kg^{-1} DW) of all biochar types. CaO in biochar increases its stability and enhances its interaction with mineral surfaces (Gui et al. 2021). Additionally, BB had the highest Fe^{2+} level (8.09 mg·kg^{-1} DW) among the plant feedstocks. Fe^{2+} is also responsible for increasing biochar stability and aiding the interaction of biochar surfaces with polyvalent metals (Jiang et al. 2022).

Animal feedstocks had considerably higher levels of mineral nutrients than the plant feedstocks. CMB had the highest levels of essential mineral nutrients for plant growth, with significantly ($p=0.000$) high NH_4-H (224.8 mg·kg^{-1}) and moderate P_2O_5 (>1.58 g·kg^{-1} DW) levels, according to the soil fertility classification (Sanchez et al. 1982). Additionally, high CaO (9.35 g·kg^{-1} DW) and Fe^{2+} (43.07 mg·kg^{-1} DW) levels ($p=0.000$) made it more stable and enhanced its interaction with mineral surfaces (Jiang et al. 2022) compared with other animal feedstocks. Moreover, ALB was similar to the CMB in terms of some of the essential nutrient levels (P_2O_5, K_2O, and MgO). However, ALB had the

Table 1 Results of the pH and electrical charge (EC) for soil and biochar types with pyrolysis temperature of 450~500 °C

Materials	pH (H$_2$O)	pH (KCl)	EC (mS/cm)
Soil	6.75	5.42	0.03
Bamboo biochar	8.79	8.10	0.84
Rice husks biochar	7.32	5.64	0.20
Woodchips biochar	8.82	7.28	0.39
Chicken manure biochar	9.86	9.41	> 4
Animal litter biochar	10.1	9.56	> 4
Sludge biochar	8.25	7.39	0.48

pH (KCl) was considered the most appropriate for the study

Table 2 Results of the chemical composition for the soil and the different biochar types. Pyrolysis temperature was 450~500 °C. Values represent the means of five replicates

Chemical properties	NH$_4$-N	NO$_3$-N	P$_2$O$_5$	K$_2$O	CaO	MgO	Fe	MnO
	(mg kg^{-1} DW*[1])	(mg kg^{-1} DW)	(g kg^{-1} DW)	(g kg^{-1} DW)	(g kg^{-1} DW)	(g kg^{-1} DW)	(mg kg^{-1} DW)	(g kg^{-1} DW)
Soil	1.00[b]	2.82[a]	0.001[f]	0.16[d]	0.51[e]	0.07[d]	1.00[d]	0.007[c]
Bamboo biochar	1.00[b]	0.37[d]	1.39[c]	0.52[b]	0.20[f]	0.23[c]	8.09[c]	0.03[bc]
Rice husks biochar	1.00[b]	0.64[c]	1.02[d]	0.49[bc]	0.56[e]	0.20[c]	1.02[d]	0.07[b]
Woodchips biochar	1.00[b]	0.18[e]	0.56[e]	0.20[d]	1.78[d]	0.065[d]	1.00[d]	0.001[d]
Chicken manure biochar	224.8[a]	0.17[e]	> 1.58[a]	>1.00[a]	9.35[a]	> 1.50[a]	43.07[a]	0.10[a]
Animal litter biochar	1.00[b]	1.69[b]	> 1.55[a]	>1.00[a]	3.39[b]	> 1.50[a]	10.32[b]	0.10[a]
Sludge biochar	1.00[b]	1.05[f]	1.48[b]	0.43[c]	2.71[c]	0.30[b]	1.00[d]	0.11[a]
Tukey test	0.000***	0.000***	0.001**	0.000**	0.000***	0.000***	0.000***	0.007**

DW dry weight

***, **, and *, significant with $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively. Tukey HSD test ($p < 0.05$) and different alphabet indicate a significant difference of mineral nutrient for the soil and each biochar[type]

highest NO_3-N levels among the animal feedstocks, indicating high organic matter in the animal feed. In comparison, SB mineral nutrient content was the lowest among the animal feedstocks.

3.3 Yield and Yield Parameters

Table 3 shows the yield, biomass, and yield parameters for the various biochar, feedstock, and vinegar treatments. The effects of location were insignificant. The yields for the control soil groups were 109.2 ton·ha^{-1} and 111.1 ton·ha^{-1} for the tomatoes without and with vinegar treatment, respectively. The yields for the SB groups were similar to those of the control groups and had the lowest results. However, the mean yields and biomass of the CMB groups, either without

(193.7 and 212.1 ton·ha^{-1}, respectively) or with vinegar (177.5 and 195.1 ton·ha^{-1}, respectively), were significantly higher than those of the other groups ($p=0.000$). The higher yields of the CMB groups were correlated with their significantly higher TFWP ($p=0.000$) (Suppl. Table 1). Additionally, the number of fruits per plant was significantly higher in the animal compared to plant feedstock groups ($p=0.049$). However, the mean yield of the animal feedstock groups was not different from those of plant feedstock groups. SFW and 100FFW were significantly higher in BB ($p=0.000$, respectively), which became evident in the plant feedstock in comparing to the animal feedstock biochar ($p=0.007$ and 0.044, respectively). Interestingly, the yield and yield parameters were not significantly different in tomatoes with and without vinegar application.

Table 3 Fruit yield (Yield), harvest index (HI), total plant weight at maturity (Biomass), number of fruit per plant (Fruit Plant^{-1}), single fruit weight (SFW), total fruit weight per plant (TFWP), and 100- fresh fruit weight (100FFW) grown with either plant or animal feedstock biochar and with or without vinegar application in 2018. Values represent the means of five replicates

	Treatments	Factors		Yield ton ha^{-1}	HI	Biomass ton ha^{-1}	Fruit Plant^{-1} #	SFW g	TFWP g	100FFW kg
Mean	No-vinegar	Location	Farmer's field	133.3	0.89	154.1	20	119.5	2427.5	11.9
			Meiwa field	142.6	0.92	155.7	20	124.6	2526.2	12.5
		Plant type	Soil	109.2	0.93	117.6	18	111.5	1965.5	11.1
			Bamboo biochar	136.9	0.90	151.5	19	132.9	2463.6	13.3
			Rice husks biochar	139.7	0.93	149.8	21	121.1	2514.6	12.1
			Woodchips biochar	138.8	0.90	154.9	19	131.4	2498.7	13.1
		Animal type	Chicken manure biochar	193.7	0.91	212.1	25	137.61	3486.1	13.8
			Animal litter biochar	160.8	0.92	175.2	21	137.98	2893.6	13.8
			Sludge biochar	107.3	0.91	117.5	21	93.45	1931.3	9.3
	Vinegar	Plant type	Soil+vinegar	111.1	0.93	119.5	19	107.1	1999.5	10.7
			Bamboo biochar+vinegar	160.0	0.92	174.7	18	160.0	2879.9	16.0
			Rice husk biochar+vinegar	159.0	0.94	169.1	22	130.1	2861.9	13.0
			Woodchips biochar+vinegar	146.1	0.90	162.1	19	136.0	2629.6	13.6
		Animal type	Chicken manure biochar+vinegar	177.50	0.91	195.10	19	125.70	2633.1	12.58
			Animal litter biochar+vinegar	149.3	0.91	163.7	21	126.0	2687.2	12.6
			Sludge biochar+vinegar	106.8	0.91	117.0	21	93.0	1922.3	9.3
		Fieldstock	Plant type	146.7	0.91	160.3	20	135.3	2641.4	13.5
			Animal type	149.2	0.91	163.4	21	118.95	2592.3	11.9
		Treatments	No-vinegar	140.9	0.91	154.1	20	123.7	2536.2	12.4
			Vinegar	144.2	0.92	157.3	20	125.4	2516.2	12.5
	ANOVA		Location (L)	0.645$^{n.s}$	0.601$^{n.s}$	0.601$^{n.s}$	0.972$^{n.s}$	0.779$^{n.s}$	0.058$^{n.s}$	0.804$^{n.s}$
			Treatments (T)	0.162$^{n.s}$	0.327$^{n.s}$	0.168$^{n.s}$	0.585$^{n.s}$	0.605$^{n.s}$	0.501$^{n.s}$	0.905$^{n.s}$
			Feedstock (F)	0.075$^{n.s}$	0.327$^{n.s}$	0.634$^{n.s}$	0.049*	0.007**	0.282$^{n.s}$	0.044*
			Biochar type (B)	0.000***	0.427$^{n.s}$	0.000***	0.009**	0.000***	0.000***	0.000***
			T × F	0.002**	0.327$^{n.s}$	0.002**	0.236$^{n.s}$	0.000***	0.000***	0.000***
			T × B	0.594$^{n.s}$	0.427$^{n.s}$	0.590$^{n.s}$	0.251$^{n.s}$	0.000***	0.252$^{n.s}$	0.000***

n.s. not significant

***, **, and *, significant with $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively

Table 4 Plant height, leaf area index (LAI), and chlorophyll estimation (SPAD) grown with either plant or animal feedstock biochar and with or without vinegar application in 2018. Values represent the means of five replicates

	Treatments	Factors		2 WAT			4 WAT		
				Plant height cm	LAI $m^2\ m^{-2}$	SPAD	Plant height cm	LAI $m^2\ m^{-2}$	SPAD
Mean	No-vinegar	Location	Farmer's field	37	0.46	53.1	49	0.52	55.9
			Meiwa field	36	0.45	55.3	49	0.56	56.5
		Plant type	Soil	36	0.43	50.3	49	0.49	51.4
			Bamboo biochar	37	0.40	56.4	50	0.61	58.7
			Rice husks biochar	31	0.36	53.5	46	0.46	54.4
			Woodchips biochar	37	0.45	58.9	50	0.66	59.9
		Animal type	Chicken manure biochar	37	0.63	56.5	53	0.66	59.6
			Animal litter biochar	35	0.46	57.4	46	0.50	58.3
			Sludge biochar	37	0.52	52.4	49	0.54	51.7
	Vinegar	Plant type	Soil+vinegar	36	0.39	49.9	49	0.49	51.5
			Bamboo biochar+vinegar	37	0.34	56.8	50	0.62	59.8
			Rice husk biochar+vinegar	31	0.30	53.2	45	0.44	54.9
			Woodchips biochar+vinegar	37	0.43	58.8	50	0.66	61.6
		Animal type	Chicken manure biochar+vinegar	37	0.61	57.9	54	0.66	59.0
			Animal litter biochar+vinegar	34	0.47	58.4	45	0.49	58.2
			Sludge biochar+vinegar	37	0.47	53.9	50	0.59	51.7
		Fieldstock	Plant type	35	0.38	56.3	49	0.58	58.2
			Animal type	36	0.53	56.1	50	0.57	56.4
		Treatments	No-vinegar	35.8	0.46	55.1	49.1	0.56	56.3
			Vinegar	35.4	0.43	55.6	49.0	0.56	56.7
ANOVA			Location (L)	$0.620^{n.s}$	$0.409^{n.s}$	$0.645^{n.s}$	$0.950^{n.s}$	$0.082^{n.s}$	$0.649^{n.s}$
			Treatments (T)	$0.054^{n.s}$	0.000^{***}	0.029^{*}	$0.905^{n.s}$	$0.527^{n.s}$	$0.321^{n.s}$
			Feedstock (F)	0.001^{**}	0.000^{***}	$0.164^{n.s}$	$0.053^{n.s}$	$0.597^{n.s}$	$0.204^{n.s}$
			Biochar type (B)	0.000^{***}	0.000^{***}	0.000^{***}	0.000^{***}	0.000^{***}	0.000^{***}
			$T \times F$	$0.506^{n.s}$	$0.645^{n.s}$	$0.620^{n.s}$	$0.555^{n.s}$	$0.905^{n.s}$	$0.134^{n.s}$
			$T \times B$	$0.154^{n.s}$	0.000^{***}	$0.938^{n.s}$	$0.069^{n.s}$	$0.804^{n.s}$	$0.912^{n.s}$

n.s. not significant

***, **, and *, significant with $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively

3.4 Plant Height, LAI, and SPAD

Table 4 shows plant height, LAI, and SPAD results for the various biochar, feedstock, and vinegar treatment groups. The effect of location was insignificant at the 2WAT and 4WAT. However, at 2WAT, plant and animal feed stocks have significantly different effects on plant height ($p=0.001$), while the mean plant height for each biochar type was only significant ($p=0.000$) for some of the plant and animal feedstocks. Plant height was higher for the BB, WB, CMB, and SB groups.

The effects of treatment, feedstock, and biochar type were all significantly higher ($p=0.000$) for LAI at 2WAT. The treatment effect was more significant ($p=0.000$)

without vinegar application by 6.5% when compared to that with vinegar application. Additionally, the LAI of tomatoes in the animal feedstock groups were significantly ($p=0.000$) higher than those of the plant feedstock groups by 28.3%, as evident for the CMB group with a mean LAI of 0.62 ($p=0.000$) (Suppl. Table 2 for statistical analyses).

Finally, for SPAD, the effects of treatment and biochar type were significant ($p=0.029$ and 0.000, respectively). SPAD of plants treated with vinegar was 0.8% higher than that of plants not treated with vinegar. The significant effect of biochar type was evident for WB with a mean SPAD value of 58.9 ($p=0.000$) (Suppl. Table 2).

At 4WAT, biochar type had a significant effect on plant height, LAI, and SPAD ($p=0.000$). Plant height was

Table 5 Growing media pH and the fresh fruit sugar/sucrose content estimation (°Brix) with either plant or animal feedstock biochar and with or without vinegar application in 2018. Values represent the means of five replicates

	Treatments	Factors		Growing media pH	Sugar content °Brix
Mean	No-vinegar	Location	Farmer's field	6.7	6.9
			Meiwa field	6.0	6.8
		Plant type	Soil	5.2	6.7
			Bamboo biochar	6.8	6.9
			Rice husks biochar	5.4	6.5
			Woodchips biochar	6.6	6.8
		Animal type	Chicken manure biochar	6.4	7.2
			Animal litter biochar	6.4	7.4
			Sludge biochar	5.4	6.7
	Vinegar	Plant type	Soil+vinegar	5.2	6.5
			Bamboo biochar+vinegar	7.0	6.9
			Rice husk biochar+vinegar	5.0	6.3
			Woodchips biochar+vinegar	6.4	6.6
		Animal type	Chicken manure biochar+vinegar	6.4	7.2
			Animal litter biochar+vinegar	6.4	7.4
			Sludge biochar+vinegar	5.2	6.0
	Fieldstock	Plant type		6.2	6.7
		Animal type		6.0	7.0
	Treatments	No-vinegar		6.0	6.9
		Vinegar		5.9	6.7
ANOVA		Location (L)		$0.129^{n.s}$	$0.810^{n.s}$
		Treatments (T)		$0.056^{n.s}$	$0.055^{n.s}$
		Feedstock (F)		$0.820^{n.s}$	$0.890^{n.s}$
		Biochar type (B)		0.000^{***}	0.000^{***}
		T × F		$1.000^{n.s}$	0.030^{**}
		T × B		$0.126^{n.s}$	$0.054^{n.s}$

n.s. not significant

***, **, and *, significant with $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively

significantly higher only for the CMB group (53.4 cm) ($p=0.000$). LAI was significantly higher for the WB and CMB groups with a mean LAI of 0.66 m²·m⁻², respectively ($p=0.000$). SPAD was significantly higher for the WB group with a mean SPAD value of 60.7 ($p=0.000$) (Suppl. Table 2).

3.5 Growth Media pH and Sugar Content

Table 5 shows the growth media pH and sugar content for the various biochar, feedstock, and vinegar treatment groups. The effects of location and treatment were insignificant. Biochar type had a significant effect on the growth media pH ($p=0.000$). Specifically, this was evident for the BB group with a mean pH of 6.9 ($p=0.000$) (Suppl. Table 3). Biochar type also had a significant ($p=0.000$) effect on the sugar content. The CMB and ALB had mean °Brix values of 7.4 and 7.2, respectively ($p=0.000$) (Suppl. Table 3).

3.6 Effectiveness of Vinegar Application for Yield and Yield Parameters

Table 6 shows the effectiveness of vinegar application on the yield, biomass, and yield parameters for the various biochar types and feedstocks. The effectiveness was positive only for the plant feedstocks, not the animal feedstocks or control soil. Specifically, it was significantly higher in terms of yield, biomass, SFW, TFWP, and 100FFW ($p=0.000–0.024$). Particularly, these values were significantly higher for the BB ($p=0.000–0.05$).

3.7 Interaction Between Wood Vinegar and Other Factors in Growth

Interactions between treatments and feedstocks ($T \times F$) were significant for the yield, biomass, SFW, TFWP,

Table 6 Effectiveness of vinegar application for tomato yield and yield parameters with either plant or animal feedstock biochar in 2018. Values represent the means of five replicates

	Factors	Biochar type	Yield ton ha^{-1}	HI	Biomass ton ha^{-1}	Fruit Plant^{-1} #	SFW g	TFWP g	100FFW kg
Mean	Plant type	Soil	1.05	1.00	1.04	1.13	0.92	1.05	0.92
		Bamboo biochar	1.43	1.04	1.38	0.95	1.51	1.43	1.51
		Rice husks biochar	1.37	1.02	1.34	1.18	1.16	1.37	1.16
		Woodchips biochar	1.12	1.01	1.10	1.04	1.07	1.12	1.07
		Chicken manure biochar	0.97	1.00	0.96	0.80	0.91	0.80	0.92
	Animal type	Animal litter biochar	0.87	0.99	0.88	1.03	0.84	0.87	0.84
		Sludge biochar	0.98	1.00	0.99	0.99	0.99	0.98	0.99
	ANOVA	Plant type	0.024*	0.067$^{n.s}$	0.020*	0.261$^{n.s}$	0.000***	0.024*	0.000***
		Animal type	0.739$^{n.s}$	0.490$^{n.s}$	1.000$^{n.s}$	0.222$^{n.s}$	0.558$^{n.s}$	0.398$^{n.s}$	0.541$^{n.s}$
	Tukey test	Vinegar effect	*	n.s	*	n.s	***	*	***

Yield fruit weight, *HI* harvest index, *Biomass* total plant weight at maturity, *Fruit Plant^{-1}* number of fruit per plant, *SFW* single fruit weight, *TFWP* total fruit weight per plant, *100FFW* 100-fresh fruit weight, *n.s.* not significant

***, **, and *, significant with $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively

Value < 1 means less effectiveness of vinegar; value > 1 means high effectiveness of vinegar

Tukey HSD test ($p < 0.05$)

100FFW, and sugar content ($p=0.000–0.030$) (Tables 3 and 5, respectively). Most parameters were higher in the plant feedstock treated with vinegar (Suppl. Fig. 1a–e), whereas sugar content was higher in the animal feedstock without vinegar treatment (Suppl. Fig. 1f)

Moreover, interactions between treatments and biochar types ($T \times B$) were significant for SFW, 100FFW, and LAI at 2WAT ($p=0.000$) (Tables 3 and 4). At 2WAT, SFW and 100FFW were greater in the BB treated with vinegar, while LAI was greater in the CMB without vinegar treatment.

4 Discussion

This study examined the effect of the interaction between vinegar and biochar feedstocks on yield and sugar content in tomato plants and whether the effectiveness of vinegar causes a lower yield and yield parameters in the presence of various feedstocks. There was a significant effect of the interaction between treatments and feedstock ($T \times F$) on yield, biomass, SFW, TFWP, 100FFW, and sugar content (Tables 3 and 5). This implies that the plant feedstock-vinegar interaction was better than the animal feedstock-vinegar interaction for most of these parameters, with the exception of the greater sugar content seen in plants treated with animal feedstock and no vinegar. The effect of the plant feedstock-vinegar interaction on yield and biomass was related to the similar interaction effect seen on TFWP. For the animal feedstock, the positive impact of the interaction on sugar content without the vinegar application was affected by the

poor sugar content of the SB under vinegar application, which tends to have a lower pH value. The feedstock variation might be related to other studies that indicate vinegar may serve as a substrate or be toxic for microbial growth and metabolism, depending on the feedstock material (Fan et al. 2022; McClellan et al. 2007).

Notably, the interaction between treatment and biochar type ($T \times B$) had a significant effect on SFW, 100FFW, and LAI at 2WAT (Tables 3 and 4). Various biochar types showed different interactions with the vinegar treatment. Notably, the SFW, 100FFW were significantly greater for the BB with vinegar application than those of other groups (Suppl. Fig. 2a and b). This may also be associated with better physiological traits of the BB, such as photosynthesis and water use efficiency, due to the higher surface area and readily available water among the biochar types (Suppl. Table 4) (Ndede et al. 2022; Zhang et al. 2017). The superiority of the BB-vinegar interaction for traits related to yield might also be supported by the higher P_2O_5 and FeO_2 levels among the plant feedstock biochars. The LAI at 2WAT was significantly greater for the CMB without vinegar application (Suppl. Fig. 2c). However, this seemed to be counterbalanced by a higher SPAD in the CMB treated with vinegar at 2WAT. The higher LAI for the CMB at early growth stages might be attributed to its high NH_4-N levels may be altered by vinegar application. Understanding these interactions is important for nitrogen use efficiency; however, the mechanism of these interactions will be discussed later.

Vinegar effectiveness in different feedstocks was clarified using yield parameters. In the plant feedstocks, vinegar

application had significantly positive effects on yield, biomass, SFW, TFWP, and 100FFW (p=0.024, 0.025, 0.000, 0.024, and 0.000, respectively) in comparison to the control and animal feedstocks (Table 6). Vinegar effectiveness on yield, biomass, SFW, TFWP, and 100FFW was evident for the BB (p= 0.05, 0.05, 0.000, 0.05, and 0.000, respectively), which is related to the existing interactions. Vinegar has been utilized for several purposes, such as crop yield improvement and foliar fertilizer (Sun et al. 2021; Zhu et al. 2021; Mungkunkamchao et al. 2013). However, concentrated vinegar has biocidal properties. Concurrently, dilute doses stimulate microbial activity due to the utilization of organic compounds (acids, aldehydes, and alcohols) as carbon sources (Fan et al. 2022; Mattos et al. 2019; Ray et al. 2022), potentially relating to the effect of vinegar on the plant feedstock biochar groups. The reduction of microbial growth in CMB by vinegar has been reported by Mohammadi-Aragh et al. (2021) and may be responsible for the negative effect of vinegar on the yield and yield parameters of the animal feedstock biochar groups, likely due to the slow conversion of NH_4-N to nitrate. Therefore, the biocidal effect of vinegar on microbes based on biochar feedstock needed to be elucidated.

Nevertheless, the yield and biomass of the CMB group were significantly higher, irrespective of the biochar material (p=0.000), which is attributed to the significantly high TFWP, in the CMB (p=0.000) (Suppl. Table 1). The superior effect of CMB over other biochar types on yield can be attributed to its abundant *in situ* mineral nutrients, particularly NH_4-N (p=0.000), which was seen through a consistently higher plant height and LAI. Chicken manure has been reported to increase the yield of maize grains more readily compared to farmyard manure (Das et al. 2022a). Similarly, the mineralization of *in situ* biochar nutrients is dependent on feedstock material (Sarfaraz et al. 2020). High-nitrogen feedstock materials, such as swine manure biochar, incorporated into soil have increased nitrogen mineralization. Soil incorporated with either wood or sewage sludge biochar, categorized as a low-nitrogen feedstock, had low and similar nitrogen mineralization. Therefore, the *in situ* mineral nutrients of biochar may serve as a complementary nutrient source. The bioavailability of biochar mineral nutrients for plant uptake might be related to the growth media pH. Das et al. (2021a, b) reported that phosphorus movement was increased in the soil column for biochar with a high pH value (6.6) used as a slow-release fertilizer. In another study, biochar increased the nodule-solubilizing sugars in maize grains (Das et al. 2022b). An excellent growth media pH for most plants, including tomatoes, should be between pH=6-7 because strong acid or weak alkaline conditions makes phosphorus form complexes with other elements such as aluminium, iron, and calcium, resulting in nutrient unavailability (Brod 2015; Bray et al. 1945). Thus, enabling mineral nutrients in biochar to be labile and available for plant uptake might require maintaining

an adequate soil pH range. The pH of the CMB and ALB remained constant (pH=6.4), regardless of the vinegar application (Table 5), likely due to their higher CaO and MgO serving as buffer agent/liming material. Limited phosphorus availability is associated with poor sugar synthesis, photosynthates, and energy (Kanayama 2017; Wu et al. 2021). This phenomenon might be related to the higher sugar content of the CMB and ALB groups (^{o}Brix=7.2 and 7.4, respectively) (Suppl. Table 3), with higher P_2O_5 and MgO contents (Kim et al. 2020). This study suggests that the use of vinegar with biochar needs careful consideration as the advantage of vinegar application in enhancing plant growth is dependent on the biochar feedstock. These findings will be helpful in selecting appropriate biochar to use in conjuncture with vinegar for tomato production to improve yield and quality.

5 Conclusion

In conclusion, our findings indicate that chicken manure biochar resulted in the highest yield, attributed to its higher ammonium-nitrogen content. Moreover, the application of vinegar positively affected the yield and yield parameters of plant feedstock groups, particularly bamboo biochar. However, animal feedstock groups, especially chicken manure biochar and animal litter biochar, demonstrated significantly higher fruit sugar content without vinegar treatment, likely due to favorable pH conditions. These results suggest that the selection of biochar and vinegar should be based on the feedstock type, as the biocidal properties of vinegar may adversely affect tomato fruit yield and quality. Overall, our study highlights the importance of considering feedstock and treatment options for optimizing biochar application in agricultural practices.

Author Contributions OI, SK, and TT conceived the idea; OI and SK designed the study; OI performed experiment; OI and EON analyzed the data; OI wrote the manuscript; OI, EON, and SK edited the manuscript; TT and KJ review the manuscript. All authors have read and approved the manuscript.

Data Availability Data will be made available on request.

Declarations

Competing Interests The authors declare no competing interests.

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