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Sustainable Substrate Management in Soilless Tomato Cultivation: Combined Effects of Biochar and Wood Distillate on Plant Growth and Fruit Mechanical Properties

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ABSTRACT

Tomato production increasingly requires high-yield plants and fruits with enhanced firmness and resistance to mechanical damage in order to reduce post-harvest losses. Pre-harvest treatments may play a key role in modulating these quality attributes. This study investigated the effect of biochar, used as a partial replacement of agriperlite (2% and 4% v/v), and wood distillate (WD) on vegetative growth, yield, fruit quality, and mechanical properties of cherry tomato (*Solanum lycopersicum* L., cv. Cikito) grown in a soilless system. Particular attention was given to mechanical parameters, including initial and mean firmness, apparent modulus of elasticity, deformation indices, absorbed energy, and elasticity. Biochar application, especially at 4% in combination with WD, significantly increased total yield and fruit number, while WD alone enhanced individual fruit weight and juice yield, particularly at the first harvest. Mechanical analyses showed that biochar improved fruit firmness and tissue stiffness, whereas WD promoted greater deformation and elasticity, indicating contrasting effects on post-harvest behavior. Fruit color varied according to harvest stage, with significant biochar–WD interactions affecting L* and b* values. Overall, the use of biochar as a partial substitute for conventional soilless substrates together with WD application, represents a promising strategy to enhance plant performance and to modulate key mechanical and technological attributes of tomato fruits. However, further optimization of WD application timing and frequency is required to ensure agronomic effectiveness while maintaining economic and environmental sustainability.

1 | Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated and consumed horticultural crops worldwide, valued

for its nutritional properties, economic relevance, and versatility in fresh and processed markets (Teshome et al. 2025). The increasing demand for high-quality produce has promoted greenhouse cultivation, which allows stable yields under

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controlled conditions, especially for high-value crops (Trépanier et al. 2025). Beyond productivity, growing attention is being directed toward pre-harvest practices capable of improving postharvest quality and reduce losses (da Silva Marques et al. 2024; Zheng et al. 2023). Tomatoes are highly perishable climacteric fruits that undergo rapid softening after harvest, making them particularly susceptible to mechanical damage during handling and transportation (Al-Dairi et al. 2021; Yadav et al. 2022). Excessive softening limits shelf-life (Al-Dairi et al. 2021) contributes to substantial postharvest losses, estimated to reach 20%–40% before consumption (Yadav et al. 2022). Improving fruit firmness through cultivation strategies is therefore a key objective to enhance postharvest performance, reduce waste, and support more sustainable production systems (Hu et al. 2020).

However, while several agronomic approaches have been explored to improve the yield and the quality, the effects of pre-harvest treatments on the mechanical properties of tomato fruits remain poorly investigated.

Wood distillate (WD), a by-product of biochar production, (Kazemi Shariat Panahi et al. 2020; Fedeli et al. 2022) contains organic acids, phenolics, and other bioactive compounds known to promote plant growth, stress tolerance, and fruit quality, although its composition varies according to pyrolysis conditions (Theapparat et al. 2014; Fedeli et al. 2023). When applied in combination with biochar, WD may exert synergistic effects that improve substrate performance and fruit development, potentially influencing fruit firmness and mechanical properties (Obadi et al. 2024).

Biochar has recently gained attention as a sustainable alternative substrate component in soilless cultivation systems, (Adhikari et al. 2025; Banitalebi et al. 2024) where conventional materials such as perlite are non-renewable and energy-intensive to extract and process (Dzięcioł et al. 2025; Pérez-Urrestarazu et al. 2019). Biochar and WD derive from agri-food waste streams and their application aligns with circular economy principles and offers opportunities to improve environmental sustainability of protected horticulture.

In this context, the present study aimed to evaluate the combined effects of WD application and partial perlite replacement with biochar on plant growth, fruit physicochemical traits, and fruit postharvest mechanical properties of tomato grown in a soilless system. Particular attention was devoted on compression testing to assess the fruit mechanical resistance, with the aim of identifying cultivation strategies that can extend shelf-life and reduce post-harvest losses.

2 | Material and Methods

2.1 | Experimental Design and Cultivation Conditions

The experiment was conducted during the spring–summer season of 2024 at the Gianguzzi farm, located in Torrenova, Sicily, Italy (38.114° N, 14.701° E). The cultivar selected for the study was “Cikito”, a cluster-type cherry tomato, characterized by elongated, date-shaped fruits with a bright red color and an average weight of 12–20 grams. This variety is commercially produced by Seminis, a brand of the Bayer Group. The plants

were grown in a soilless greenhouse, using a soilless cultivation system with 100% cultivation bags containing agriperlite (0BC), supplied by Agripan (<https://www.perlite.it/>). To evaluate biochar as a potential partial replacement for agriperlite, commercial biochar provided by Biodea S.r.l. (Arezzo, Italy, <https://www.biodea.bio/>) was incorporated into the substrate at two volumetric concentrations: 2% (2BC) and 4% (4BC). The characteristics of the biochar are reported in Table S1.

Tomato seedlings were initially sown in a local nursery and subsequently transplanted into the grow bags. The trial consisted of five grow bags per treatment, each containing three plants (15 plants per treatment).

Half of the plants received a root-dipping treatment at transplanting using a wood distillate (WD) solution (300 mL/hL), followed by biweekly fertigation with WD at 0.5 kg/1000 m² and weekly foliar sprays (200–250 mL/hL, depending on developmental stage). The composition of WD is shown in Table S2. Control plants (0WD) received only the standard nutrient solution used by the farm, whose formulation is reported in Table S3. The fertigation solution and substrate had pH values of 5.5–6.0 and 5.5–6.5, respectively, and electrical conductivity (EC) values of 2.4 mS cm^{−1} for the solution and 2.5–3.0 mS cm^{−1} for the substrate. The experimental treatments are summarized in Figure 1, where the combinations of wood distillate application (0WD = no wood distillate; WD = wood distillate treatment) and biochar percentage (0BC = 0%; 2BC = 2%; 4BC = 4%) are indicated.

2.2 | Plant Growth Measurements

Each plant was measured for height using a measuring tape from the base of the stem to the apical meristem on three dates: May 6, 2024 (36 Days After Transplanting, DAT), May 21, 2024 (51 DAT), and August 19, 2025 (141 DAT), before apical pruning. On the first two sampling dates, the number of leaves per plant was also recorded up to the time of defoliation, an agronomic practice commonly employed to enhance fruit ripening uniformity by improving light penetration within the canopy (Raya et al. 2024).

2.3 | Fruit Harvesting and Sampling Protocol

Fruits were harvested at full maturity, following the standard practice adopted by the farm, when they reached the red-ripe stage. Because this variety has indeterminate growth, fruits were harvested in three harvest dates: from the basal trusses (2nd–5th; 26 June 2024), the medial trusses (6th–10th; 11 July 2024), and the apical trusses (11th–15th; 31 July 2024), as carried out by Agosti et al. (2025). Representative photographs illustrating plant management and fruit development during the experiment are provided in the supporting material (Figure S1).

2.4 | Fruit Morphological and Physical Measurements

For each treatment and harvest, fruits were randomly divided into three batches, and five fruits per batch (15 total) were selected. Fruits were weighed using a Mettler Toledo balance

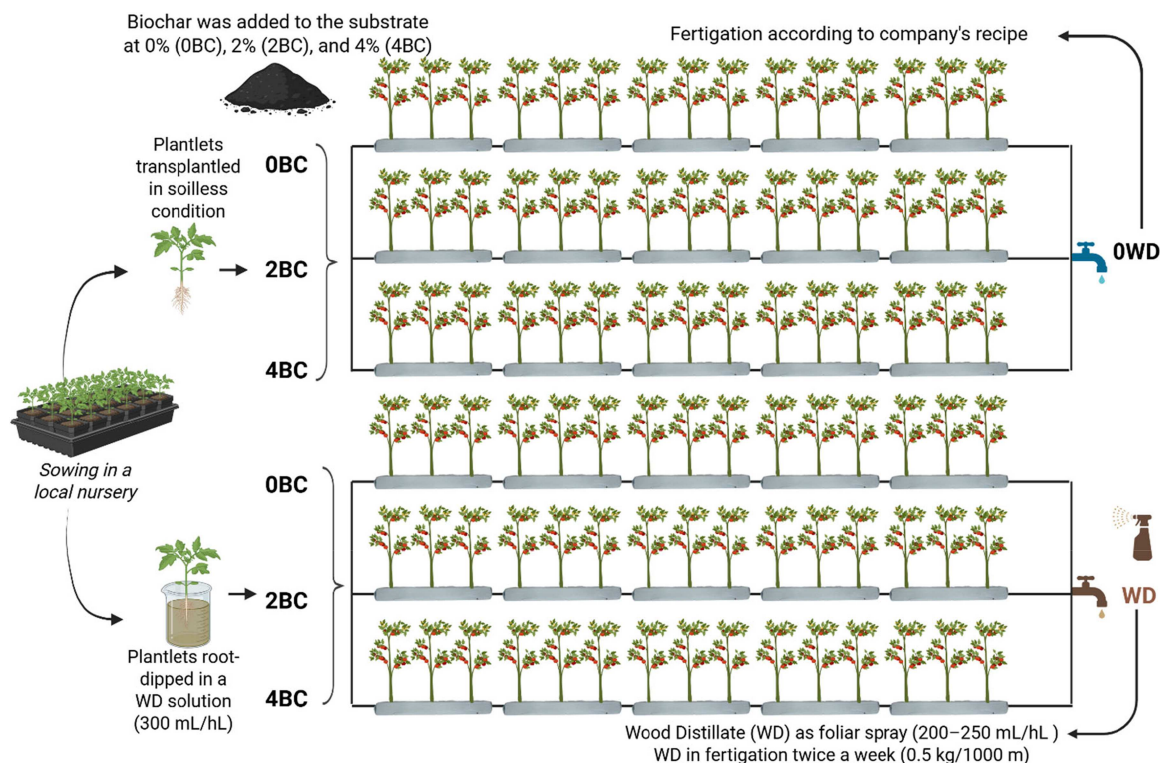


FIGURE 1 | Overview of the experimental design. Tomato plantlets were transplanted into a soilless system. Plants either received no wood distillate (OWD) or were treated with WD through root-dipping at transplanting and later via foliar spray and fertigation (WD). Both WD conditions were combined with three levels of biochar incorporated into the substrate (0%, 2%, and 4%; 0BC, 2BC, 4BC).

(PB 5001-S), and equatorial (ED) and longitudinal (LD) diameters were measured with a digital caliper (Vogel Germany GmbH & Co. KG).

Fruit color was assessed at each harvest using a Minolta CR-200 colorimeter, with results expressed in the CIELab space, where L^* indicates lightness and a^* and b^* represent the green-red and blue-yellow axes, respectively (Pérez-López et al. 2006, 2007). Measurements were taken on the equatorial surface after gently removing moisture, and mean values were calculated from 15 fruits per harvest.

Mechanical properties were evaluated on an additional set of 15 fruits per treatment and harvest, selected for comparable size and weight. Compression tests were performed assuming deformation on one side only, using a texture analyzer (ZwickiLine Z0.5 TN, ZwickRoell S.r.l., Genoa, Italy) equipped with a 50 N (5 kg) load cell (precision class 0.5). Fruits were positioned horizontally and subjected to a double compression cycle between flat plates (150 mm diameter), at a deformation rate of 10 mm min^{-1} and maximum force of 19.6 N (F_{max}). A 30 s stress-relaxation phase followed the second compression.

Firmness parameters were derived from the force–deformation curve ($\Delta F/\Delta D$): Initial Firmness (IF) was defined at 0.25 kg resistance, while Mean Firmness (MF) corresponded to the $\Delta F/\Delta D$ ratio, representing the force required to produce 1 mm deformation (N mm^{-1}) (Table S4).

Figure S2 shows typical examples of the force–deformation curve, which illustrates how the sample responds during compression, and the relaxation curve, which describes how the sample behaves once the applied force is released.

From the compression data, the following parameters were calculated:

- Relaxation ratio (L_1/L_2);
- Absorbed energy, corresponding to the area enclosed by the double compression cycle;
- Degree of elasticity (AB/OB);
- Deformation ratio ($OB/\text{initial fruit diameter}$);
- *Modulus* of elasticity (E), calculated according to Equation (1):

$$E = 9.81 \sqrt{\frac{(1.125(1 - \mu^2)^2 \Delta F^2)}{D^3(AD/10)}} \quad (1)$$

where μ is the Poisson's ratio (Hetzroni et al. 2011) and expressed as Equation (2)

$$\mu = 0.5M + 0.1 \frac{(100 - M)}{100} \quad (2)$$

M is the average moisture content of the tomato (%), D is the equatorial diameter (mm), and 9.81 represents the gravitational acceleration constant. The empirical constant 1.125 was used according to the standard formula.

Texture data were processed using TestXpert III ZwickRoell, which managed data acquisition, automatic parameter calculation, and standardized reporting to ensure repeatable test conditions.

2.5 | Statistical Analysis

Data processing was carried out using JASP (version 0.19.3.0). Statistical analyses were performed by means of two-way ANOVA, with “WD Treatment” and “% Biochar” as fixed factors. For plant growth parameters (plant height and leaf number), fruit morphological traits, juice yield, color variables, and mechanical properties obtained from compression tests, separate two-way ANOVAs were run for each measurement date or harvest date. When significant main effects or interactions were detected, pairwise comparisons were conducted using Tukey's HSD post hoc test, with statistical significance set at $p \leq 0.05$.

3 | Results and Discussion

3.1 | Effects on Plant Growth and Yield

Plant showed a progressive increase throughout the crop cycle, from early May (H1 and H2) to mid-August (H3), when the plants were topped (Table 1).

At H1 and H2, plant height was mainly influenced by the factor “WD Treatment”, with WD treated-plants exhibiting slightly reduced height compared to untreated ones (H1: 83.2 ± 3.8 cm vs. 79.7 ± 5.6 cm; H2: 150.3 ± 5.7 cm vs. 141.7 ± 8.3 cm). This effect may reflect an early modulation of vegetative growth induced by WD application. At H3, a significant interaction between the factors “WD Treatment” and “% Biochar” was observed with increased plant height associated with biochar application, particularly when combined with WD (Table 1). Similar behavior have been reported by Jabborova et al. (2021), who observed increased plant height in ginger (*Zingiber officinale*) grown on substrates enriched with biochar, suggesting a positive role of biochar in supporting vegetative growth under soilless conditions.

Leaf number per plant was recorded shortly after transplanting (beginning of May, L1) and prior to the onset of major vegetative growth (end of May, L2). Two-way ANOVA revealed a significant interaction between the two factors only for L1. The highest number of leaves was recorded in plants grown without BC and without WD treatment, although 2BC0WD plants did not differ significantly from 0BC0WD plants or from the other treatments (Table 1). For L2, the negative effect of “WD Treatment” on leaf production was confirmed, with a significant reduction in the number of leaves produced (L2: 22.4 ± 0.8 vs. 21.7 ± 1.3).

Total plant yield and fruit number per plant were influenced by the interaction between “WD Treatment” and “% Biochar” (Table 1). Yield was positively affected by the combined application of biochar and WD treatment, particularly in 2BC plants, where WD treatment resulted in a marked yield increase (+67%). This trend is consistent with previous reports showing yield enhancement following WD application (Ofae et al. 2022), and biochar incorporation in soilless systems (de Celis et al. 2025). At the same time, the observed responses appear to be cultivar- and substrate-dependent, as reported by Agosti et al. (2024). These findings suggest that interactions between genotype, substrate composition, and biostimulant application may play an important role in determining yield outcomes (French and Iyer-Pascuzzi 2018).

TABLE 1 | Effect of Wood Distillate and Biochar Treatment on growing and productive parameters.

WD Treatment	% Biochar	H1 (cm)	H2 (cm)	H3 (cm)	L1 (n°)	L2 (n°)	Plant/yield (g)	N° fruits/plant
0WD	0BC	83.60 ± 4.69	150.10 ± 6.24	273.00 ± 12.85 b	15.00 ± 0.66 a	22.06 ± 0.51	2634.59 ± 448.63 ab	181.33 ± 15.02 bc
	2BC	84.50 ± 2.46	150.40 ± 4.32	266.60 ± 4.55 b	14.40 ± 0.69 ab	22.50 ± 0.52	2099.75 ± 233.97 b	178.66 ± 15.87 bc
	4BC	81.60 ± 4.42	150.60 ± 6.50	278.40 ± 6.02 b	13.80 ± 0.78 b	22.60 ± 1.34	2857.14 ± 155.63 ab	248.00 ± 10.44 a
WD	0BC	81.50 ± 4.27	146.00 ± 8.52	270.90 ± 12.18 b	13.60 ± 0.69 b	22.10 ± 1.10	2470.71 ± 44.55 ab	176.33 ± 3.52 c
	2BC	81.10 ± 5.56	142.60 ± 10.90	272.20 ± 4.15 b	13.60 ± 0.69 b	21.70 ± 1.88	3506.88 ± 49.64 a	265.33 ± 18.22 a
	4BC	76.50 ± 6.98	136.50 ± 5.62	298.60 ± 12.89 a	13.70 ± 0.67 b	21.30 ± 0.94	3250.20 ± 80.18 a	237.33 ± 5.54 ab
Statistical analysis of the factors								
WD Treatment (WD)		0.008	< 0.001	0.002	< 0.001	0.005	0.100	0.041
% Biochar (BC)		0.053	0.154	< 0.001	0.056	0.548	0.116	< 0.001
WD×BC		0.630	0.103	0.002	0.019	0.548	0.012	0.004

Note: Two-way ANOVA followed by Tukey's test ($p \leq 0.05$). Within each parameter, different letters indicate statistically significant differences. Results are expressed as mean ± standard deviation. WD Treatment indicates treatments without (0WD) or with (WD) wood distillate. % Biochar (BC) indicates the different biochar percentages in the substrate: 0% (0BC), 2% (2BC), and 4% (4BC). H1 = plant height at 36 DAT, H2 = plant height at 51 DAT, H3 = plant height at 141 DAT, L1 = n° of leaves at 36 DAT, L2 = n° of leaves at 51 DAT.

TABLE 2 | Effect of “WD Treatment” and “% Biochar” on fruits Fresh Weight (FW), Equatorial diameter (ED), Longitudinal diameter (LD), juice yield and color parameters, during the harvest season.

WD Treatment	% Biochar	FW (g)	ED (mm)	LD (mm)	Juice Yield (ml)	L*	a*	b*
1st harvest date								
OWD	OBC	13.55 ± 0.14	24.08 ± 0.01	36.11 ± 0.83	118.00 ± 2.82	32.45 ± 0.77	24.40 ± 0.05	19.22 ± 0.99
	2BC	13.55 ± 1.55	24.27 ± 1.16	39.10 ± 0.14	124.70 ± 25.45	33.95 ± 0.33	23.13 ± 0.62	17.65 ± 0.33
	4BC	12.14 ± 0.14	23.35 ± 0.12	34.55 ± 0.10	108.85 ± 3.60	33.07 ± 0.09	23.40 ± 0.56	17.68 ± 0.35
WD	OBC	16.37 ± 0.56	25.66 ± 0.08	37.615 ± 0.99	155.45 ± 12.94	33.47 ± 0.05	23.40 ± 0.53	17.59 ± 0.19
	2BC	17.53 ± 0.27	25.49 ± 0.09	40.04 ± 0.13	164.80 ± 5.65	34.12 ± 0.09	22.73 ± 0.37	16.87 ± 0.60
	4BC	14.49 ± 0.85	24.22 ± 0.61	36.025 ± 0.86	123.50 ± 4.94	33.53 ± 0.19	23.17 ± 0.28	17.17 ± 0.33
Statistical analysis of the factors								
WD Treatment (WD)		0.003	0.008	0.007	0.005	0.101	0.282	0.069
% Biochar (BC)		0.059	0.146	< 0.001	0.039	0.055	0.296	0.151
WD×BC		0.567	0.671	0.563	0.336	0.481	0.780	0.580
2nd harvest date								
OWD	OBC	16.77 ± 1.88	25.60 ± 1.20	38.00 ± 2.16	146.50 ± 0.98 a	31.12 ± 0.05 ab	23.75 ± 0.10	17.82 ± 0.17 ab
	2BC	14.95 ± 0.80	24.94 ± 0.27	35.65 ± 0.63	128.80 ± 1.97 ab	33.61 ± 0.22 b	24.38 ± 0.36	17.99 ± 0.18 a
	4BC	14.70 ± 0.14	24.77 ± 0.45	35.66 ± 0.42	139.35 ± 0.91 a	33.73 ± 0.02 ab	23.08 ± 0.10	17.09 ± 0.03 abc
WD	OBC	14.36 ± 1.25	24.32 ± 1.01	33.56 ± 0.96	136.80 ± 11.17 a	33.58 ± 0.25 b	23.69 ± 0.21	16.74 ± 0.20 bc
	2BC	14.18 ± 0.20	24.50 ± 0.35	35.51 ± 0.49	135.30 ± 3.67 ab	34.05 ± 0.03 ab	23.47 ± 0.51	16.18 ± 0.30 c
	4BC	12.77 ± 0.21	23.33 ± 0.17	34.25 ± 0.83	115.70 ± 4.52 b	34.50 ± 0.07 a	24.75 ± 0.26	18.04 ± 0.22 a
Statistical analysis of the factors								
WD Treatment (WD)		0.080	0.040	0.019	0.025	0.099	0.375	0.008
% Biochar (BC)		0.258	0.241	0.567	0.023	0.165	0.741	0.137
WD×BC		0.711	0.586	0.076	0.019	0.009	0.113	0.001
3rd harvest date								
OWD	OBC	11.15 ± 0.42 abc	22.83 ± 0.14 ab	32.31 ± 1.46	102.35 ± 9.68 ab	34.61 ± 0.10 b	22.88 ± 0.25	16.82 ± 0.37
	2BC	13.02 ± 0.54 a	23.89 ± 0.46 a	33.15 ± 1.20	123.00 ± 7.91 a	34.73 ± 0.10 ab	23.13 ± 0.12	17.18 ± 0.24
	4BC	10.31 ± 0.16 bc	22.24 ± 0.29 bc	31.45 ± 0.25	99.80 ± 0.28 ab	35.44 ± 0.21 ab	24.59 ± 0.23	18.22 ± 0.09
WD	OBC	9.18 ± 0.47 c	21.13 ± 0.57 c	30.56 ± 0.42	86.35 ± 5.35 b	35.48 ± 0.25 a	24.64 ± 0.82	18.66 ± 0.69
	2BC	9.88 ± 0.46 bc	21.27 ± 0.32 c	30.66 ± 0.43	88.50 ± 0.30 b	34.86 ± 0.05 ab	24.38 ± 0.72	18.48 ± 0.74
	4BC	12.13 ± 0.24 ab	23.17 ± 0.32 ab	33.58 ± 0.13	116.95 ± 5.15 a	34.90 ± 0.06 ab	23.77 ± 0.24	18.15 ± 0.03
Statistical analysis of the factors								
WD Treatment (WD)		0.016	0.002	0.188	0.029	0.271	0.114	0.033

(Continues)

TABLE 2 | (Continued)

WD Treatment	% Biochar	FW (g)	ED (mm)	LD (mm)	Juice Yield (ml)	L*	a*	b*
% Biochar (BC)		0.042	0.076	0.255	0.055	0.113	0.624	0.613
WD×BC		0.002	0.001	0.115	0.005	0.010	0.077	0.177

Note: Two-way ANOVA, Tukey's post-hoc test ($p \leq 0.05$). Within each parameter and each harvest date, different letters indicate statistically significant differences. Results are expressed as mean $\pm$ standard deviation. WD Treatment indicates treatments without (OWD) or with (WD) wood distillate. % Biochar (BC) indicates the different biochar percentages in the substrate: 0% (0BC), 2% (2BC), and 4% (4BC). L* (lightness), a* (red-green), and b* (yellow-blue) — during the harvest season.

Abbreviations: ED = Equatorial Diameter, FW = Fresh Weight, LD = Longitudinal Diameter.

The number of fruits per plant was higher in 2BC plants treated with WD and in 4BC plants without WD (Table 1). While the positive influence on BC fruit number has been reported for other crops grown soilless, such as cucumber (*Cucumis sativus* L.) (Venkataramani et al. 2023), information regarding the specific effects of WD on fruit set remains limited, indicating the need for further investigation.

3.2 | Effects on Fruit Morphological and Physicochemical Traits

Fruit is known to be strongly influenced by truss position in tomato plants (Agosti et al. 2025; Tsouvaltzis et al. 2023; He et al. 2022). Accordingly, treatment effects in the present study varied across harvest dates corresponding to basal, medial, and upper trusses (Table 2).

The fruit weight (FW) showed considerable variability during the harvesting period, in agreement with previous observations (Kechasov et al. 2021). At the first harvest, FW was higher in WD-treated plants (on average +23%) regardless of biochar application. No significant differences were detected at the second harvest, whereas at the final harvest a significant interaction between factors emerged (Table 2). Fruits with the highest FW were obtained from 2BC plants without WD and from 4BC plants treated with WD, although these values were not significantly different from those of the control. Neither the BC nor the WD exerted a strong influence on FW across harvests, confirming previous findings in tomato (Graber et al. 2010) and highlighting cultivar-specific responses to biochar reported in other species.

The fruit size is influenced by multiple factors, including agronomic practices (Tsouvaltzis et al. 2023; Bertin et al. 2002) such as substrate composition and foliar fertilization (Lovatt 1999; Tijskens et al. 2020). In the present study, the fruit ED was influenced by “WD Treatment”, for the first and second harvests (Table 2). Specifically, WD application determined a 5% increase of ED at the first harvest and a –4% decrease in the second. In the final harvest, ED was influenced by the interaction between factors; specifically, within plants treated with WD, ED values were statistically higher in 4BC than those from 0BC plants, confirming the synergistic effect of biochar and wood distillate previously demonstrated by other authors (Becagli et al. 2022; El-Fawy et al. 2024). For the fruit LD, at the first harvest, both factors exerted independent effects (Table 2), with a +4% increase in fruits from WD treated plants and a +7% increase for fruits from 2BC plants, compared to those from 0BC. At the second harvest only the WD treatment had a significant impact (Table 2), leading to a 5.5% reduction in LD. To the best of authors’ knowledge, no previous studies have examined the effects of both biochar and wood distillate application on fruit size, across successive harvests.

Although indeterminate tomato cultivars, such as the one used in this study, are predominantly appreciated by consumers for fresh consumption, evaluating their juice yield is of interest when assessing their suitability for industrial processing, as it directly affects both the efficiency of industrial production and the economic value of the final product (Eslami et al. 2024). This is especially relevant for tomato sauce production, a sector in which Italy is a global leader (Cannata et al. 2024; Morra

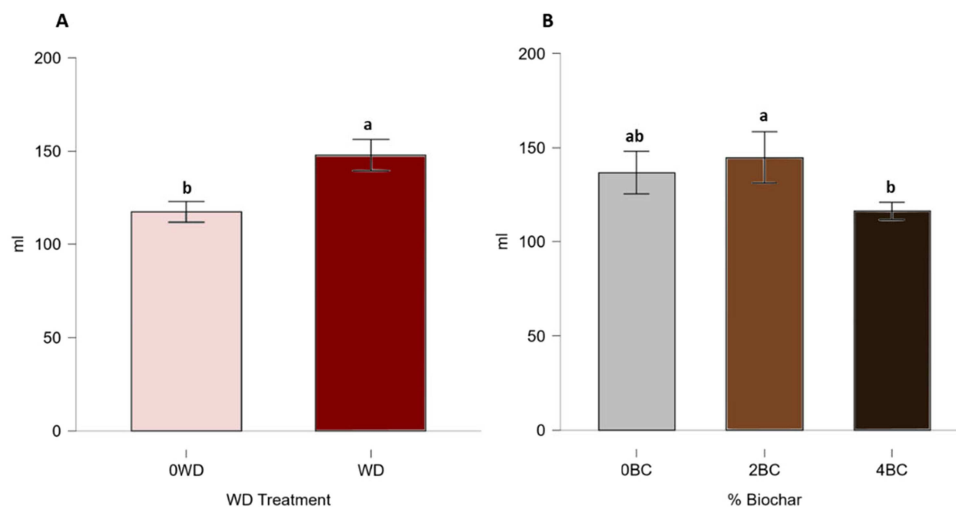


FIGURE 2 | Effect of (A) “WD Treatment” and (B) “% Biochar” on juice yield expressed in mL, during the 1st harvest date.

et al. 2021). At first harvest, a single effect of “WD treatment” and “% Biochar” on juice yield was observed (Table 2). Specifically, WD treatment enhanced tomato juice yield (+26%), while BC either did not influence (at 2%) or reduces (at 4%) this parameter (Figure 2). For the second and third harvest dates, in 0WD plant biochar did not appear to affect the juice yield. In contrast, when WD was distributed, fruits from 4BC plants showed a particularly interesting behavior: their juice yield was significantly lower at the second harvest, but then increased at the third harvest, reaching values comparable to those of 0BC0WD plants (Table 2).

The color of tomato fruits, expressed through the CIELab parameters (L^* , a^* , b), is an important quality attribute that reflects the ripeness and appearance of the fruit (Panebianco et al. 2023). Since several studies have shown that agricultural practices and treatments can influence different fruit quality parameters (Pérez-López et al. 2007), the following results describe the effects of “WD treatment” and “% Biochar” on the color characteristics of the harvested fruits. Regarding lightness (L^*), the statistical analysis revealed a significant interaction between “WD Treatment” and “% Biochar” at the second and third harvests. Results confirm what was already stated that biochar alone did not influence the fruit lightness; whereas, when WD was distributed, fruits from BC-treated plants maintained a more stable lightness than those from 0BC plants. Notably, lightness in 0BCWD fruits was significantly higher than in 0BC0WD fruits (Table 2).

For the a^* parameter, no significant differences were observed among treatments during the entire harvest period (Table 2). Also for this parameter, it is worth to underline that results reported in this study are in contrast with those of Agosti et al. (2024), in which tomato fruits, cv. Solarino, harvested from 5BC plants exhibited values of a^* statistically higher than those from other treatments, confirming the cultivar-specific plant response to WD and BC. The b^* parameter, similarly to L^* , showed statistically significant differences at the second and third harvest. Specifically, at the second harvest the analysis revealed a significant interaction between the factors, with an +8% increase in fruits collected from plants treated with 4BC and WD compared with those treated with 0BC and WD (Table 2). At the third harvest, a significant main effect of the

“WD Treatment” was observed, with plants treated with WD showing an average increase of b^* values of approximately +6% in fruits from WD treated plants compared to untreated plants.

3.3 | Effects on Fruit Mechanical Properties

Mechanical testing provides direct information on fruit texture and structural integrity, which are critical for postharvest handling and storage (Ahmet et al. 2016). Compression test was therefore used to assess the mechanical behavior of tomato fruits subjected to different pre-harvest treatments.

The apparent modulus of elasticity (E_a) is a mechanical parameter that describes the overall stiffness of biological tissues (Shirvani et al. 2014; Ghonimy et al. 2025). Understanding this parameter is crucial, since excessive compression can damage tissues and lower product value. At the first harvest, statistical analysis highlighted an interaction between the tested factors (Table 3). Fruits collected from 4BC plants, WD treated, exhibited a higher E_a , compared to 0BC0WD plants. At the second harvest, only the “% Biochar” exhibited a significant effect, with fruits of 4BC plants showing a +28% increase in E_a compared to those from 0BC plants. At the third harvest, WD treatment did not affect E_a in BC-treated plants, whereas, in 0BC plants, WD reduced E_a values by approximately 25% (Table 3).

Firmness is a key quality trait, reflecting tissue resistance to deformation and determining texture, transportability, shelf-life, and consumer acceptance (Manivel-Chávez et al. 2011). Initial Firmness (IF) indicates the stiffness and texture of the fruit, while Mean Firmness (MF) is a measure of the material's resistance to deformation under an applied load, reflecting the force required to reach the point of sudden fracture (Sirisomboon et al. 2012). Both parameters provide valuable information about the texture and structural integrity of the fruit. Regarding the Initial Firmness (IF), an interaction was observed between factors, at the first harvest (Table 3). Fruits harvested from 2BC plants without WD treatment, presented an IF statistically higher (+57%) compared to that of 0BC plants. At the second harvest, a significant effect of the “% Biochar” was observed, with fruits from 4BC plants presenting an IF significantly higher (+42%) than that of fruits from 0BC plants

TABLE 3 | Effect of “WD Treatment” and “% Biochar” on Compression test parameters.

WD Treatment	% Biochar	Ea (KPa)	IF (Nmm ⁻¹)	MF (Nmm ⁻¹)	Absorbed Energy (Nmm)	Degree of elasticity (%)	Deformation at Fmax (mm)	Deformation ratio
1st harvest date								
OWD	0BC	1.28 ± 0.10 c	2.83 ± 0.27 b	4.65 ± 0.30 ab	38.51 ± 4.84	0.53 ± 0.02 b	4.23 ± 0.25 ab	0.11 ± 0.01
	2BC	2.30 ± 0.18 ab	4.45 ± 0.22 a	5.53 ± 0.31 a	33.31 ± 3.10	0.73 ± 0.03 a	3.55 ± 0.18 b	0.13 ± 0.01
	4BC	2.08 ± 0.08 b	3.05 ± 0.27 b	4.60 ± 0.28 ab	40.06 ± 3.56	0.76 ± 0.03 a	4.32 ± 0.29 ab	0.16 ± 0.01
WD	0BC	2.25 ± 0.19 ab	3.14 ± 0.29 b	4.61 ± 0.26 ab	42.66 ± 1.87	0.69 ± 0.02 a	4.23 ± 0.20 ab	0.18 ± 0.008
	2BC	1.75 ± 0.06 c	2.44 ± 0.61 b	4.01 ± 0.58 b	40.06 ± 3.56	0.75 ± 0.03 a	4.88 ± 0.27 a	0.20 ± 0.01
	4BC	2.77 ± 0.23 a	3.47 ± 0.44 ab	5.28 ± 0.45 ab	33.68 ± 4.16	0.74 ± 0.03 a	3.73 ± 0.28 b	0.17 ± 0.02
Statistical analysis of the factors								
WD Treatment (WD)		<0.001	0.058	0.273	0.198	0.032	0.238	0.014
% Biochar (BC)		0.718	0.222	0.618	0.916	<0.001	0.664	0.377
WD×BC		<0.001	<0.001	0.006	0.171	0.028	0.002	0.275
2nd harvest date								
OWD	0BC	1.28 ± 0.04	2.51 ± 0.13	2.46 ± 0.19 b	73.50 ± 5.30	0.64 ± 0.04 b	7.90 ± 0.66 a	0.12 ± 0.01
	2BC	1.67 ± 0.14	2.60 ± 0.48	3.74 ± 0.53 ab	49.51 ± 12.92	0.77 ± 0.01 a	5.47 ± 0.80 b	0.14 ± 0.02
	4BC	1.72 ± 0.09	3.70 ± 0.59	3.96 ± 0.26 a	41.12 ± 1.01	0.71 ± 0.01 ab	4.93 ± 0.35 b	0.19 ± 0.03
WD	0BC	1.46 ± 0.04	2.13 ± 0.16	3.66 ± 0.18 ab	50.74 ± 6.61	0.77 ± 0.02 a	5.30 ± 0.30 b	0.16 ± 0.02
	2BC	1.43 ± 0.01	2.47 ± 0.17	3.38 ± 0.09 ab	47.07 ± 0.87	0.72 ± 0.01 ab	5.73 ± 0.13 b	0.14 ± 0.01
	4BC	1.68 ± 0.06	3.03 ± 0.41	3.72 ± 0.20 ab	40.98 ± 0.60	0.75 ± 0.04 a	5.23 ± 0.27 b	0.18 ± 0.01
Statistical analysis of the factors								
WD Treatment (WD)		0.614	0.222	0.399	0.129	0.029	0.112	0.083
% Biochar (BC)		0.005	0.037	0.051	0.018	0.199	0.025	0.155
WD×BC		0.063	0.775	0.032	0.188	0.004	0.010	0.192
3rd harvest date								
OWD	0BC	1.79 ± 0.02 a	3.19 ± 0.46	3.97 ± 0.14 ab	39.36 ± 1.62	0.72 ± 0.02	4.83 ± 0.24 b	0.10 ± 0.01
	2BC	1.49 ± 0.07 ab	2.34 ± 0.31	3.00 ± 0.02 bc	76.85 ± 10.65	0.70 ± 0.04	6.50 ± 0.50 ab	0.16 ± 0.01
	4BC	1.52 ± 0.09 ab	3.89 ± 0.77	4.85 ± 0.57 a	38.28 ± 4.27	0.75 ± 0.02	4.07 ± 0.49 b	0.13 ± 0.01
WD	0BC	1.33 ± 0.03 b	2.46 ± 0.34	2.17 ± 0.03 c	92.87 ± 6.70	0.60 ± 0.02	8.86 ± 0.07 a	0.19 ± 0.01
	2BC	1.75 ± 0.19 ab	2.33 ± 0.39	3.34 ± 0.57 abc	62.49 ± 23.75	0.67 ± 0.08	6.30 ± 1.35 ab	0.17 ± 0.02
	4BC	1.41 ± 0.06 ab	2.15 ± 0.29	2.99 ± 0.30 bc	63.35 ± 18.74	0.74 ± 0.03	6.53 ± 0.67 ab	0.13 ± 0.02
Statistical analysis of the factors								
WD Treatment (WD)		0.216	0.049	0.003	0.076	0.149	0.003	0.185

(Continues)

TABLE 3 | (Continued)

WD Treatment	% Biochar	Ea (KPa)	IF (Nmm ⁻¹)	MF (Nmm ⁻¹)	Absorbed Energy (Nmm)	Degree of elasticity (%)	Deformation at Fmax (mm)	Deformation ratio
% Biochar (BC)		0.322	0.347	0.078	0.364	0.186	0.109	0.377
WD×BC		0.010	0.214	0.018	0.078	0.403	0.029	0.146

Note: Two-way ANOVA, Tukey's post-hoc test ($p \leq 0.05$). Within each parameter and per each harvest date, different letters indicate statistically significant differences. Results are expressed as mean $\pm$ standard deviation. WD Treatment indicates treatments without (0WD) or with (WD) wood distillate. % Biochar (BC) indicates the different biochar percentages in the substrate: 0% (0BC), 2% (2BC), and 4% (4BC). Abbreviations: Ea = Apparent modulus of elasticity, IF = Initial Firmness, MF = Mean Firmness.

(Figure 3A). At the final harvest, the decrease of the IF values was determined by “WD Treatment” (Table 3, Figure 3B).

Considering MF, for all three harvest dates, a general negative effect exerted by the WD treatment was observed (Table 3). The reduction in MF was particularly evident, both at the first and third harvest, respectively, in fruits from 2BC and 4BC plants, both treated with, highlighting the not particularly positive influence of WD on fruit mean firmness. The IF and MF trends observed in this study align with Suthar et al. (2018), who found that 3% bamboo biochar enhanced tomato firmness. However, to the best of our knowledge, no previous work has simultaneously evaluated both Initial Firmness and Mean Firmness in response to a combined biochar–wood distillate treatment, underscoring the novelty of our findings.

Another parameter assessed was Absorbed energy (Ae), which reflects the mechanical work needed to deform the fruit. Higher Ae indicates greater energy storage before failure, although not all of this energy leads to bruising, as some is dissipated elastically or viscously (Van Zeebroeck et al. 2007). In this study, Ae was not affected by either the “WD Treatment” or the “% Biochar”, except during the second harvest, in which “% Biochar” was the only factor influencing fruit response, with a significant reduction of Ae in fruits from 4BC (Table 3). This reduction in Ae may suggest that these fruits are less suitable for transportation due to their greater susceptibility to bruising. Nevertheless, considering that other quality traits can be enhanced by biochar application, this remains an interesting and relevant finding.

The Degree of Elasticity represents the ability of a material, in this case tomato fruit, to recover its original shape after being subjected to deformation (Sirisomboon et al. 2012), thus indicating the proportion of reversible versus permanent deformation. In this study, at the first and second harvest, an interaction was observed between factors (Table 3). At the first harvest date, fruits from all treated plants exhibited a higher Degree of Elasticity compared with the fruits without treatment (0BC and 0WD), with an average increase of +36%. From the second to the third harvest, the differences between treated and untreated fruits became less pronounced (Table 3). Deformation, defined as the strain at the point of maximum applied force, indicates the fruit's mechanical resilience and its capacity to withstand compressive loads without failing (Sirisomboon et al. 2012). Lower Deformation at Fmax values reflect greater resistance under maximum load, which is beneficial for mechanical strength and transport. Statistical analysis showed an interaction between factors across all harvest dates (Table 3). At the first and at the third harvest dates, the from the statistical analysis, it was not possible to formulate a unique interpretation of the factor influence on the fruit response; instead, at the second harvest, Fmax of treated fruits, both with or without WD, was significantly lower than untreated fruits (0BC0WD), on average –32%. In a recent study by Ghonimy et al. (2025), higher deformation was associated with fruits having higher water content, suggesting that fruits with more water tend to exhibit lower stiffness and are more prone to deformation.

The Deformation ratio represents the extent of fruit deformation under an applied force relative to its original size, providing a measure of the fruit's strain and its response to mechanical loading (Sirisomboon et al. 2012). Statistical analysis revealed a notable effect of “WD Treatment” at the first harvest date, for this parameter; in fact, the fruits treated with WD exhibited an

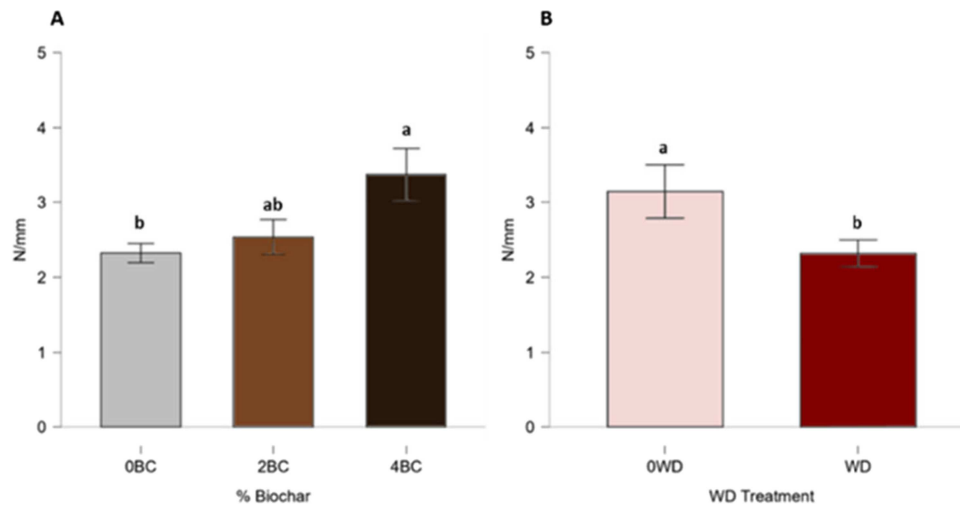


FIGURE 3 | (A) Effect of “% of Biochar” on initial firmness (IF) at the 2nd harvest; (B) Effect of “WD Treatment” on IF at the 3rd harvest.

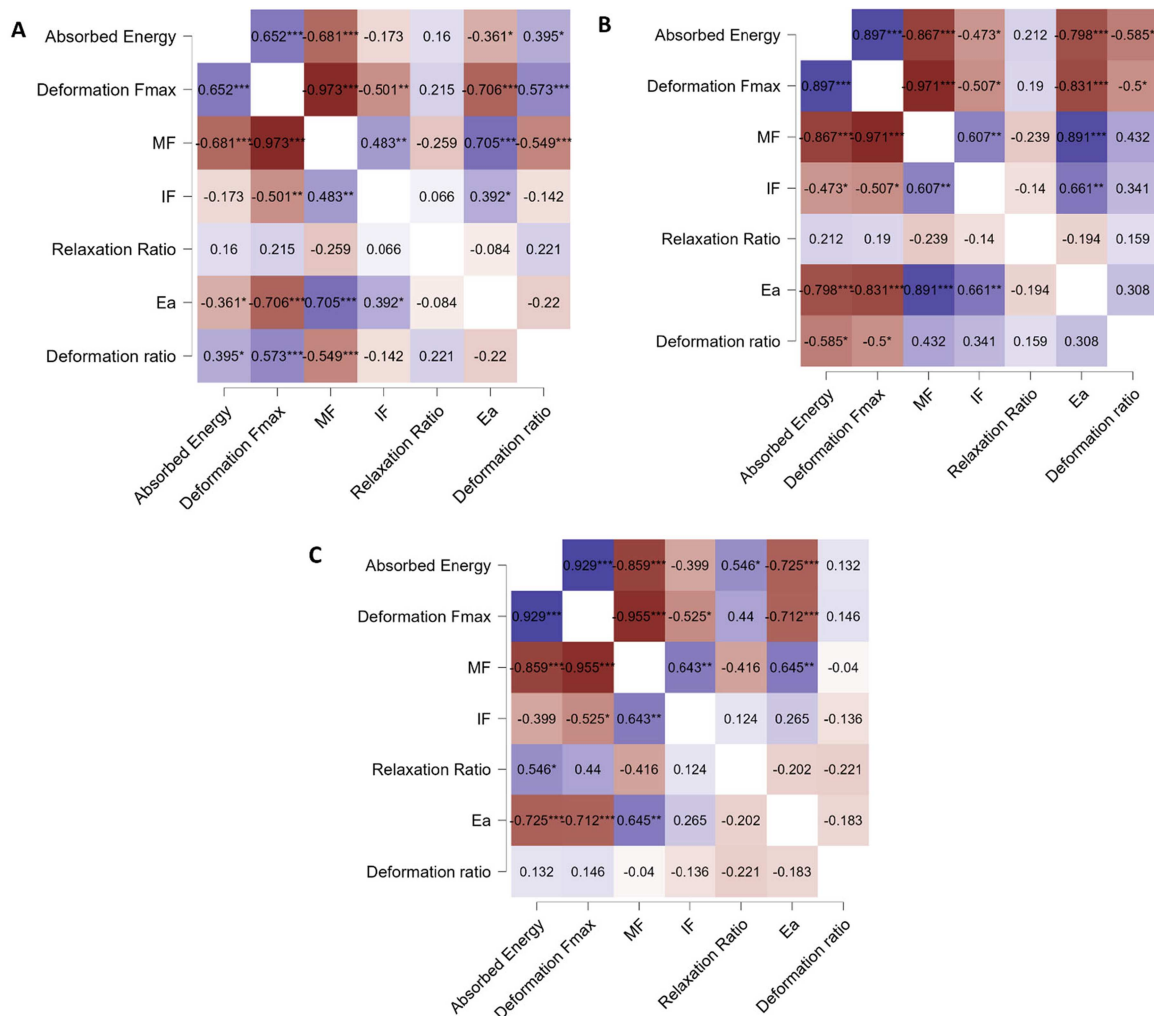


FIGURE 4 | Pearson correlation heatmaps of compression parameters of fruits at (A) first, (B) second, and (C) third harvest.

increased deformation ratio. A high deformation ratio is generally unfavorable for mechanical strength and transport, as such fruits are more prone to bruising. However, from a sensory perspective, it may be considered positive, as it reflects softer and riper fruits.

3.4 | Correlation Analysis of Mechanical Parameters

Correlation analysis clearly revealed that mechanical parameters-dependent relationships linked to harvest date (Figure 4). At the first harvest (A), a strong positive

correlation was observed between Deformation at Fmax and Absorbed Energy, while both parameters were negatively correlated with firmness-related variables (IF and MF). This trend suggests that fruits requiring greater deformation to reach failure also absorbed more energy, but exhibited lower firmness.

At the second harvest (B), the correlations between firmness and the other parameters became stronger and more negative, indicating that fruits from the upper trusses exhibited lower firmness than those from the lower and medial trusses, despite being harvested at the same maturity stage. In contrast, the deformation-related variables (Degree of Elasticity, Deformation Ratio, and Deformation at Fmax) showed consistent positive correlations with one another.

At the third harvest (C), most correlations were weaker, suggesting a more heterogeneous mechanical behavior among fruits from upper trusses. The negative associations between firmness and deformation parameters remained evident, confirming that softer fruits tend to deform more easily under compressive loads.

These patterns indicate that the mechanical response of tomato fruits varies throughout the harvesting season and is influenced by both truss position and pre-harvest treatments.

4 | Conclusion

The present study demonstrated that the combined use of biochar and wood distillate significantly influenced vegetative growth, yield, and fruit physical-mechanical properties in soilless cherry tomato cultivation. Wood distillate alone reduced early plant height but increased fruit weight and juice yield, particularly at the first harvest, while biochar at 2% and 4% enhanced plant growth and productivity, with synergistic effects when combined with wood distillate.

Fruit quality was also affected by the treatments. Color responses varied across harvests, with the 4% biochar and wood distillate showing the most pronounced effects, while juice yield displayed interaction-dependent trends throughout the production cycle. Mechanical analysis indicated that biochar increased fruit firmness and tissue stiffness, whereas wood distillate promoted greater deformation and elasticity, resulting in softer fruits. The observed inverse relationship between firmness, deformation, and absorbed energy, highlights the dynamic mechanical behavior of ripening tomatoes.

These results indicate that pre-harvest application of biochar and wood distillate can improve yield and modulate fruit mechanical properties relevant to post-harvest handling, with potential implications for shelf life and waste reduction.

Further research is required to optimize application strategies in order to achieve agronomically effective and economically sustainable management practices.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The raw data supporting the conclusions of this article are not included but will be made available by the authors upon request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Figure S1: Representative photographs illustrating plant management and fruit development during the experiment. **Figure S2:** Typical force–deformation and relaxation curves from tomato fruit compression tests. **Table S1:** Characteristics of the biochar used in this study declared by the producer. **Table S2:** Characteristics of the wood distillate used in this study declared by the producer. **Table S3:** Composition of the fertigation solution. **Table S4:** Meaning of compression parameters.