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Citrus Waste as a Sustainable Amendment for Tomato Soilless Substrates Under Deficit Irrigation

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Abstract

The citrus processing industry generates large amounts of organic residues whose sustainable management is a major environmental challenge. The aim of this study was to evaluate the effects of incorporating citrus-derived waste (CW) into coconut-coir-based substrates on tomato (*Solanum lycopersicum* L., cv. Proxy) under different irrigation regimes (I) in a factorial design (CW × I) with three replications. Each replicate consisted of six plants (pots), and the replicate was considered the experimental unit. Plants were grown in substrates amended with 0%, 6.25%, 12.5%, 25.0%, and 37.5% (*v*/*v*) citrus waste and subjected to three water regimes (100%, 75%, and 50% of the standard water supply). Plant growth, biomass allocation, yield components, and fruit quality traits were assessed. Results indicate that CW can be incorporated into coconut-coir substrates without detectable penalties in total production at low-to-moderate rates (6.25–12.5%) across all irrigation regimes. Yield reductions of 18% (from 3398 to 2789 g plant^{-1}) attributable to CW were observed mostly at the highest inclusion rates under moderate deficit irrigation (75% water supply), whereas under severe deficit (50% water supply), production declined across all CW rates, including 0%, indicating that water deficit has a dominant limiting effect. Fruit quality parameters were generally maintained or improved in amended substrates, particularly under reduced irrigation with deficit irrigation, generally increasing total soluble solids at 100%, 75%, and 50% WC (+13%, +19%, and +9%, respectively). Overall, these findings support the use of citrus waste at low-to-moderate proportions as a sustainable amendment for soilless tomato cultivation without marked negative effects on yield and fruit quality, enabling its use as a locally sourced substrate component within circular-economy strategies.

Keywords: water deficit; organic waste management; yield components; fruit quality

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1. Introduction

The citrus industry represents a major segment of the agri-food sector, with citrus fruits among the most widely cultivated fruit crops worldwide [1]. Citrus production spans more than 150 countries, mainly located in tropical and subtropical regions, covering approximately 10.6 million hectares [2]. As of 2024, global citrus production has increased over the last decade, reaching 165 million metric tons, with oranges as the dominant species (40% of total citrus production), followed by mandarins/tangerines (31%), and lemons/limes (14%) [2]. A substantial share of citrus fruit is destined for industrial processing, primarily juice production and essential oil extraction, typically ranging from ~20% on

average to ~40–50% depending on species and region [2–4]. Industrial processing generates large amounts of residues, commonly estimated at 50–60% of the processed fruit mass, including peels, pulp, seeds, pomace, citrus wax, and wastewater [4–6]. In Europe, citrus production is highly concentrated in the Mediterranean basin; Spain and Italy account for most of the EU supply, and Italy alone averages ~3 million tons year^{-1}; citrus waste (CW) exceeds 500,000 t per year [7]. Overall, these figures highlight the magnitude and relevance of citrus-derived waste streams and motivate the development of scalable and environmentally sound valorization routes.

The processing stage generates residues rich in soluble sugars, pectin, cellulose, hemicellulose, phenolics, and essential oils. When improperly disposed of, these materials pose significant environmental and economic challenges because of their rapid fermentability and high oxygen demand [8–10]. Despite these critical issues, citrus residues constitute a valuable renewable resource that aligns with the principles of the circular economy and sustainable bioresource valorization [11]. Recent studies highlight their potential for conversion into a wide range of bio-products, including bioactive extracts, nanocellulose, biopolymers, biofuels, and agronomic amendments, through integrated biorefinery approaches [12,13].

Among the various strategies explored, the agronomic valorization of citrus waste stands out as a promising solution capable of simultaneously enhancing soil fertility and reducing the environmental burden of agro-industrial disposal [14]. The incorporation of citrus peel-derived materials into agricultural systems has been shown to improve soil organic matter, nutrient availability, and the activity of beneficial microbiota, while contributing to sustainable orchard management [3,7]. More broadly, natural organic amendments, such as composts, plant residues, and agro-industrial by-products, are recognized for their ability to enhance soil physical structure, increase water-holding capacity, promote nutrient cycling, and support microbial activity, thereby improving crop performance under both optimal and stress conditions [15].

In soilless cultivation systems, interest in organic-based substrates is rapidly increasing as an alternative to conventional materials such as peat and coconut coir. Composted agro-industrial residues have demonstrated valuable properties when incorporated into growing media, including slow-release nutrient supply, improved porosity, and enhanced biological activity [16]. Studies using food-waste or agro-industrial composts indicate that, when properly blended, these materials can support vigorous seedling development and biomass accumulation in various horticultural species [17,18]. Moreover, substituting conventional substrates with locally sourced citrus-derived amendments and readily available Mediterranean by-products in major producing regions not only increases substrate sustainability but also contributes to lowering greenhouse gas emissions by reducing waste disposal requirements and long-distance transport of imported materials, further reinforcing the environmental benefits of circular bioeconomy strategies.

Despite its potential, the use of CW in soilless media may involve several constraints. Depending on processing and pre-treatment methods, CW may exhibit elevated soluble salt concentrations, variable pH, and the presence of phenolic compounds and essential-oil residues that could exert phytotoxic effects [19]. In addition, the high organic fraction may affect the C/N balance of the substrate. For these reasons, CW incorporation rates must be carefully optimized to balance agronomic benefits with potential chemical and physical risks.

In soilless horticulture, coconut coir is among the most widely used substrates; however, it is largely imported from Asian countries (mainly from India and Sri Lanka), resulting in high economic costs and a substantial carbon footprint associated with long-distance transport [20]. The partial substitution of coconut coir with locally available agro-industrial

residues could represent a promising strategy to reduce environmental impacts and improve the sustainability of soilless production systems [21].

Water management represents another critical aspect of sustainable horticulture. Irrigation accounts for more than 70% of global freshwater consumption, and improving water-use efficiency is a major priority for modern agriculture [15]. Deficit irrigation strategies, in which water supply is intentionally reduced relative to crop evapotranspiration, are widely adopted to save water but often result in yield reduction, suboptimal growth, or altered fruit quality [22]. The use of organic amendments has been repeatedly shown to mitigate drought effects by enhancing substrate water retention, improving soil structure, and moderating nutrient availability, thereby contributing to improved plant resilience under reduced water supply [15].

Despite extensive research on citrus waste valorization and the agronomic benefits of organic amendments, their application as structural components of soilless substrates, particularly in combination with irrigation deficit strategies, remains poorly investigated. Given their high content of fibrous polymers and pectic substances, citrus waste may enhance the water-holding properties of growing media and potentially exert a compensatory effect under water-limited conditions [3,7].

The present study investigates plant growth, yield, and fruit quality by evaluating the incorporation of different percentages of citrus waste (0% to 37.5% *v*/*v*) into a coconut-coir-based growing medium for the soilless cultivation of tomato (*Solanum lycopersicum* L.) under three irrigation regimes (100%, 75%, and 50% of the standard water supply). We hypothesized that citrus waste can partially replace coconut coir without agronomic penalties at realistic blending rates, and that its effects on yield components and fruit quality are modulated by water availability. By integrating waste valorization with water-saving management, this work contributes to advancing sustainable horticultural practices and to the development of innovative circular-economy substrates for high-efficiency soilless production systems.

2. Materials and Methods

2.1. Experimental Site and Plant Material

A greenhouse experiment was conducted at a commercial farm located in Milazzo (ME) from September 2024 to April 2025. Tomato seedlings, at the two-true-leaf stage, were transplanted into black plastic pots (Ø20, 5 L) filled with coconut fiber and different rates of CW (0%, control, 6.25%, 12.5%, 25.0%, and 37.5% on a volumetric basis) under three levels of water content (100% WC, 75% WC, and 50% WC). The commercial F1 hybrid tomato 'Proxy' (ISI Sementi S.p.A., Fidenza, Italy), resistant to Fusarium wilt and widely used as a reference for the mid-plum type, was used. Plants were grown at a density of 1.5 plants m^{-2}.

Relative air humidity was always high, ranging from 72 to 95%, and the average daily temperature varied from 15 to 35 °C throughout the experimental period.

Due to the high moisture content, citrus waste was air-dried to a moisture content of 20% before the start of the experiment to facilitate handling and ensure homogeneous incorporation into the substrate. Before filling the pots, CW was thoroughly mixed with the coconut fiber at different inclusion rates, and the pots were then filled for the different treatments. Bumblebees (*Bombus* spp.) were used to promote fruit set.

The experiment was arranged in a 2-way randomized complete block design (citrus waste rate x irrigation regime) with 3 replications. Each replication consisted of six plants (pots).

Fruits from the first cluster were harvested at commercial maturity, corresponding to 80 days after transplanting, when they had reached the light-red color stage. The harvests

were carried out progressively until the eighth cluster reached maturity. Following each harvest, fruits were separated from the rachis and classified as marketable or unmarketable, including malformed or cracked fruits. Total fruit production was determined as g plant^{-1}. Measurements included fruit number, individual fruit weight and size, as well as total and marketable yield. At the end of the experimental trial, plants from each treatment were separated into stems, leaves, and roots. Dry biomass was determined after oven-drying at 80 °C for 72 h until a constant weight. Aboveground dry biomass included leaves plus stems. The root–shoot ratio was determined as the ratio of root dry weight to aboveground dry weight.

Fruit quality analyses were performed on samples collected from the second and sixth clusters, which ripen under different microclimatic conditions during fall and winter [23].

2.2. Citrus Waste

Citrus waste was collected from a citrus processing industry (Messina, Italy). It consisted of the waste produced by the citrus processing plant. The waste and the commercial coconut fiber were characterized to determine their main chemical elements and heavy metals (to exclude potential contamination and any confounding effects on plant responses) (Table 1). Heavy metal concentrations were within acceptable ranges and were therefore unlikely to bias the experimental outcomes.

Table 1. Main chemical parameters determined on citrus waste (CW).

Parameter	CW	Coconut Fiber	Directive
dry matter (d.m.) (%)	33.4	91.7	Gravimetric method
pH	6.7	6.2	UNI EN ISO 10523:2012 [24]
Organic matter (% d.m.)	91	89	DM 13/09/99
N (% d.m.)	2.3	0.2	CNR IRSA 6 Q 64 Vol. 3
P (% d.m.)	0.7	0.015	CNR IRSA 6 Q 64 Vol. 3
K (g/kg d.m.)	1.69	0.744	UNI EN 13657:2004 [25] + EPA 6010 D 2018 [26]
Mg (g/kg d.m.)	0.12	1.06	UNI EN 13657:2004 [25] + EPA 6010 D 2018 [26]
Ca (g/kg d.m.)	0.42	4.61	UNI EN 13657:2004 [25] + EPA 6010 D 2018 [26]
C/N	23.1	258	------
Cd (mg/kg d.m.)	<0.5	<0.5	ANPA 15—Man. N. 3/2001
Cu (mg/kg d.m.)	9.34	<0.5	ANPA 15—Man. N. 3/2001
Ni (mg/kg d.m.)	4.44	0.63	ANPA 15—Man. N. 3/2001
Pb (mg/kg d.m.)	7.67	<0.5	ANPA 15—Man. N. 3/2001
Zn (mg/kg d.m.)	19.15	14	ANPA 15—Man. N. 3/2001
Cr (mg/kg d.m.)	2.19	0.89	ANPA 15—Man. N. 3/2001
Hg (mg/kg d.m.)	<0.5	<0.5	ANPA 15—Man. N. 3/2001

2.3. Irrigation System

The trial was carried out under a drip irrigation system. Irrigation scheduling was regulated by a lysimetric control system that continuously monitored plant pot weight and automatically triggered irrigation events. In the control treatment, plants received 100% of their estimated water requirement (100% WC), while deficit irrigation treatments supplied 75% and 50% of the control irrigation volume, respectively, by reducing the applied volume per irrigation event, while maintaining the same scheduling logic. Irrigation events were triggered to restore the substrate to the target moisture range. The 100% water requirement was defined operationally as the irrigation volume needed to maintain readily available water at approximately 10% and a drainage fraction between 10% and 15%. This system dynamically adjusted irrigation according to climatic conditions, while maintaining the prescribed reduced irrigation levels. Fertigation was performed uniformly to all treatments

using a complete nutrient solution containing macronutrients (mmol L^{-1}): 13.59 NO_3^-–N, 1.42 NH_4^+–N, 2.21 PO_4^{3-}–P, 7.23 K^+, 5.28 Ca^{2+}, 2.99 Mg^{2+}, and 4.87 SO_4^{2-}–S, as well as micronutrients (µmol L^{-1}): 18.44 Fe^{2+}, 34.72 B, 0.96 Cu^{2+}, 6.40 Zn^{2+}, 12.01 Mn^{2+}, and 0.72 Mo, with an electrical conductivity of 1.9 dS m^{-1} and a pH ranging from 5.5 to 6.2.

2.4. Fruit Shape Index and Color

The longitudinal (L) and transverse (D) diameters of the fruits were determined using a digital caliper. Fruit shape was expressed as the fruit shape index (FSI), calculated as the ratio between the maximum fruit length and width (L/D), following the approach described by Brewer et al. [27].

Tomato color was evaluated by measuring lightness (L*), red–green coordinate (a*), and yellow–blue coordinate (b*) using a CR-200 colorimeter (Konica Minolta, Inc., Tokyo, Japan).

2.5. Total Soluble Solids (TSS)

Total soluble solids (TSS), expressed as °Brix, were determined using a portable digital refractometer (Hanna Instruments, Woonsocket, RI, USA). Before use, the refractometer was calibrated by adding a few drops of distilled water (0 °Brix).

2.6. pH, Titratable Acidity, and Maturity Index

An aliquot of 30 g of the mashed tomato samples was homogenized using an Ultraturrax T18 homogenizer (Janke & Kunkel, IKA Instruments, Staufen, Germany), quantitatively transferred to Falcon tubes, and centrifuged at 1250× *g* for 10 min. The supernatant was filtered through Whatman 90 papers and used to determine pH and titratable acidity.

The pH was measured using a benchtop XS pH 8 standard pH meter (XS Instruments, Carpi, MO, Italy), equipped with a Hamilton Polyte Lab electrode (Hamilton, Bonaduz, Switzerland).

For titratable acidity (TA), a 10 mL aliquot of each tomato juice was manually titrated with 0.1000 N NaOH using phenolphthalein (1% ethanolic solution) as an indicator until the pink endpoint. The titratable acidity was expressed as % of citric acid and calculated according to the following expression:

$$\text{TA (\% citric acid)} = (\text{V(mL) of NaOH} \times 0.64)/(\text{V(mL) of tomato juice})$$

For each tomato sample, the maturity index was calculated by dividing its total soluble solids (TSS) by the titratable acidity (TA) [28].

2.7. Data Analysis

The experimental data were organized and calculated using Microsoft Excel version 2025 software. Prior to ANOVA, normality of residuals was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using Levene's test. Analysis of variance (ANOVA), including two-way ANOVA, was performed using Minitab software version 19. Tukey's test ($p < 0.05$) was applied to determine significant differences among groups. Measurements were collected on six plants per replicate; statistical analyses were performed on replicate means, with the replicate considered as the experimental unit.

3. Results

3.1. Plant Biomass

Interaction effects between irrigation (I) regime and citrus waste percentage (CW) were not significant for any of the biomass-related parameters; therefore, only main effects are discussed. Plant growth and biomass allocation were significantly affected by irrigation

regime, while citrus waste percentage had no significant effects on most biomass parameters compared to the control substrate (Table 2).

Table 2. Total dry weight (leaf, stem and root) (g plant^{-1}), aboveground dry weight (leaf and stem) (g plant^{-1}), leaf, stem and root dry weight (g plant^{-1}), and root to shoot ratio in the tomato cv Proxy grown greenhouse under optimal irrigation (100% WC), medium water deficit irrigation (75% WC), and severe water deficit irrigation (50% WC) and different percentage of CW (0%, 6.25%, 12.5%, 25.0%, and 37.5%).

Treatments		Total Dry Weight (g plant^{-1})	Aboveground Dry Weight (g plant^{-1})	Leaf Dry Weight (g plant^{-1})	Stem Dry Weight (g plant^{-1})	Root Dry Weight (g plant^{-1})	R/S Ratio
Irrigation (I)	100% WC	240.7 ± 8.1 A	214.7 ± 7.1 A	142.2 ± 5.8 A	72.5 ± 2.2 A	26.0 ± 3.0	0.12 ± 0.01 B
	75% WC	213.6 ± 11.5 A	187.8 ± 12.0 A	128.1 ± 11.1 A	59.7 ± 1.8 B	28.2 ± 2.5	0.16 ± 0.02 AB
	50% WC	168.6 ± 5.0 B	139.4 ± 5.0 B	89.2 ± 3.5 B	50.2 ± 2.8 C	28.5 ± 3.4	0.21 ± 0.03 A
Citrus Waste (CW)	0%	222.6 ± 16.0	188.9 ± 14.6	129.3 ± 10.6	59.5 ± 5.7 AB	32.7 ± 3.2 A	0.18 ± 0.02
	6.25%	210.3 ± 14.4	174.9 ± 15.4	119.2 ± 12.6	55.7 ± 3.6 B	35.4 ± 2.7 A	0.22 ± 0.03
	12.5%	210.4 ± 19.8	188.6 ± 20.3	128.3 ± 17.9	60.3 ± 3.3 A	21.8 ± 2.4 B	0.13 ± 0.02
	25.0%	206.0 ± 13.3	177.0 ± 11.8	115.3 ± 9.0	61.7 ± 3.7 A	23.2 ± 3.7 B	0.13 ± 0.02
	37.5%	188.8 ± 9.8	164.0 ± 13.2	107.0 ± 9.5	57.0 ± 4.6 B	24.9 ± 4.9 B	0.18 ± 0.05
Significance							
I		***	***	***	***	ns	**
CW		ns	ns	ns	*	**	ns
I × *CW*		ns	ns	ns	ns	ns	ns

Values are mean ± SE. Asterisks indicate a significant effect of water irrigation (I), citrus waste percentages (CW), and their interaction (I × CW) according to ANOVA. ns = not significant; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Different letters indicate significant differences based on Tukey's test ($p < 0.05$).

Total, aboveground, and leaf dry weights progressively decreased with increasing water deficit, with plants grown under 50% WC showing significantly lower biomass compared to those grown under 100% WC and 75% WC. Stem dry weight appeared particularly sensitive to reduced irrigation, showing a significant decrease even at 75% WC.

The root-to-shoot ratio increased significantly under reduced irrigation, indicating a shift in biomass allocation toward belowground organs in response to water limitation.

Citrus waste percentage did not significantly affect total or aboveground biomass compared to the control substrate. Stem dry weight was influenced by CW levels, with the 12.5–25.0% treatments showing the highest values, whereas 6.25% and 37.5% exhibited lower stem dry weight, and the control (0%) was intermediate. No significant interaction between irrigation regime and CW percentage was observed for biomass-related parameters.

Root dry weight was influenced by CW percentage, with the highest values observed in the 0% and 6.25% treatments, while significantly lower root biomass was recorded at CW levels ranging from 12.5% to 37.5%. No significant interaction between factors was observed (Table 2).

3.2. Yield Components and Fruit Production

Tomato yield and its components were significantly influenced by both irrigation regime and citrus waste incorporation rate, with clear and consistent interaction effects between the two factors for total production, total fruit number, and marketable fruit number (Table 3; Figure 1).

Table 3. Total, production (g plant^{-1}), Total fruit number (n plant^{-1}), Marketable fruit number (n plant^{-1}), Average fruit weight (g fruit^{-1}), and fruit shape index in the tomato cv Proxy grown greenhouse under optimal (100% WC irrigation), medium water deficit irrigation (75% WC), and severe water deficit irrigation (50% WC) and different percentage of CW (0%, 6.25%, 12.5%, 25.0%, and 37.5%).

Treatments		Total Production (g plant^{-1})	Total Fruit Number (n plant^{-1})	Marketable Fruit (n plant^{-1})	Average Fruit Weight (g fruit^{-1})	Fruit Shape Index (FSI)
Irrigation (I)	100% WC	3459.7 ± 87.1 A	98.4 ± 2.3 A	94.3 ± 2.8 A	39.9 ± 0.9 A	0.84 ± 0.01 AB
	75% WC	3195.5 ± 97.1 A	88.6 ± 1.5 B	88.1 ± 1.6 B	38.4 ± 0.9 A	0.85 ± 0.01 A
	50% WC	2262.6 ± 87.6 B	71.3 ± 1.4 C	68.9 ± 1.3 C	33.0 ± 0.8 B	0.83 ± 0.01 B
Citrus Waste (CW)	0%	3120.6 ± 198.3 A	86.0 ± 3.8 A	85.8 ± 3.9 AB	39.0 ± 0.8	0.85 ± 0.01
	6.25%	3079.3 ± 257.3 A	88.8 ± 5.2 A	87.2 ± 5.7 A	37.8 ± 1.1	0.85 ± 0.01
	12.5%	2787.0 ± 192.4 A	88.9 ± 3.3 A	79.9 ± 3.4 AB	37.0 ± 1.2	0.84 ± 0.01
	25.0%	3101.0 ± 200.6 A	87.4 ± 5.4 A	86.9 ± 5.4 A	36.0 ± 1.2	0.83 ± 0.01
	37.5%	2775.1 ± 196.3 B	79.7 ± 3.3 B	79.1 ± 3.5 B	35.7 ± 1.3	0.83 ± 0.01
Significance						
I		***	***	***	*	*
CW		*	**	*	ns	ns
I × *CW*		**	*	*	ns	ns

Values are mean ± SE. Asterisks indicate a significant effect of irrigation (I), citrus waste percentages (CW), and their interaction (I × CW) according to ANOVA. ns = not significant; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Different letters indicate significant differences based on Tukey's test ($p < 0.05$).

As expected, total production, total fruit number, and marketable fruit number declined progressively with increasing water deficit. Plants grown under severe deficit irrigation (50% WC) exhibited a marked reduction in yield and average fruit weight (2262.6 g m^{-2} and 33.0 g fruit^{-1}, respectively) compared with those grown under full irrigation (3459.7 g m^{-2}; 39.9 g fruit^{-1}). Total fruit number and marketable fruit number were already significantly reduced under moderate deficit irrigation (75% WC) and showed a further decline under severe water deficit (50% WC), confirming the strong sensitivity of tomato productivity to water availability. Fruit shape index (FSI) showed only minor variations among irrigation treatments, indicating limited effects of water deficit on fruit morphology.

When averaged across irrigation regimes, low-to-moderate CW incorporation (6.25–12.5%) maintained yield levels comparable to the control, whereas only the highest amendment rate (37.5%) resulted in a significant reduction in total production. Total fruit number and marketable fruits were significantly and negatively affected only at the highest CW percentage.

Significant irrigation × CW interactions were detected for yield and fruit number, indicating that the response to citrus waste amendment depended on water availability.

As illustrated in Figure 1, the interaction between irrigation regime and citrus waste incorporation rate significantly influenced tomato yield, fruit number, and marketable fruit number. However, the extent of statistically significant differences among CW treatments varied depending on the irrigation level.

Under full irrigation conditions (100% WC), total production, total fruit number, and marketable fruit number showed only minor differences among CW treatments, belonging to the same significance group, with values remaining within a narrow range across the amendment gradient (3460 g plant^{-1}, 98.4 n plant^{-1}, and 94.3 n plant^{-1}, respectively). This indicates that, under non-limiting water supply, differences among CW were statistically negligible.

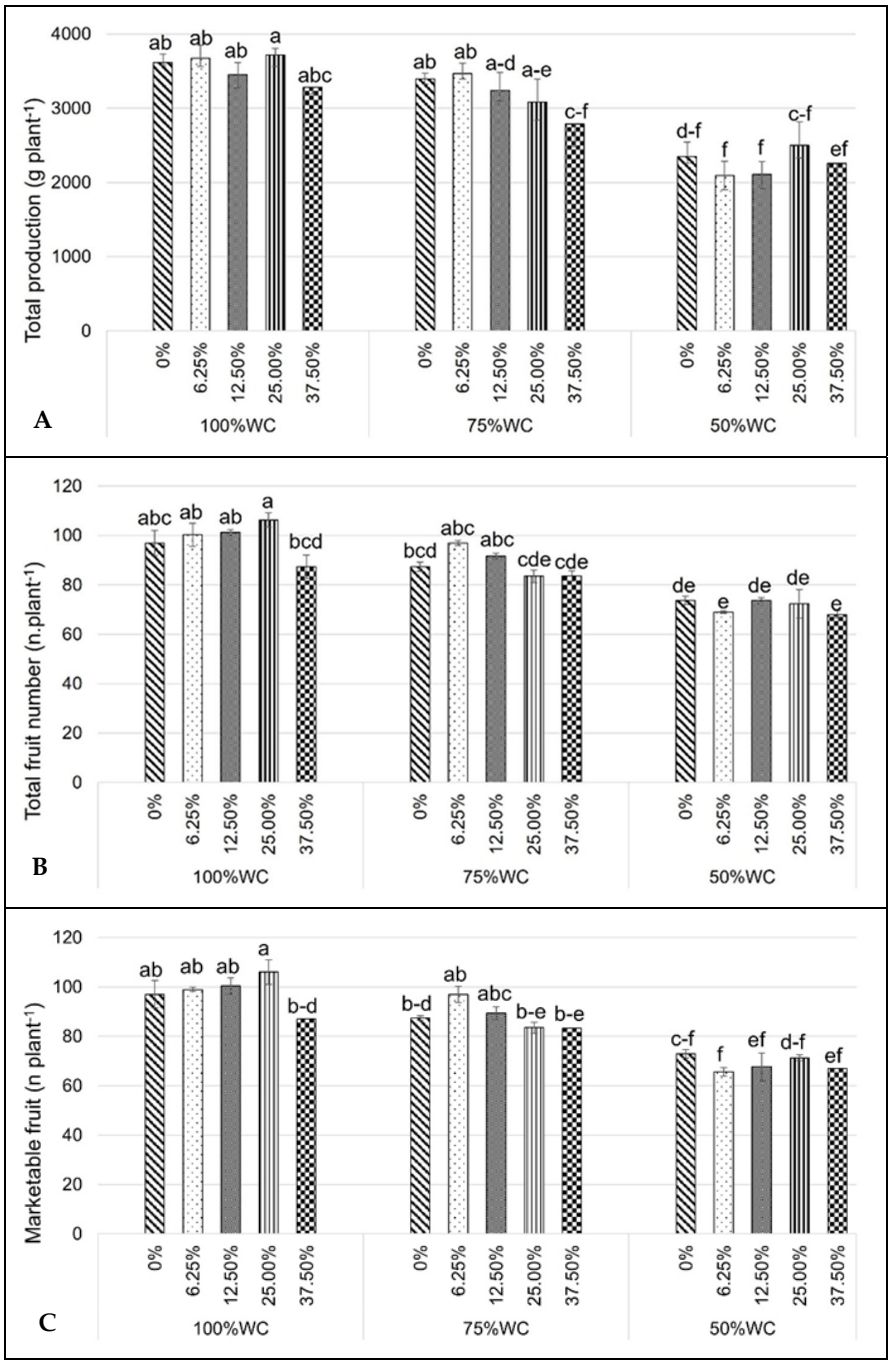

Figure 1. Interaction effects of water treatments and citrus waste percentages (CW) on total production (**A**), total fruit number (**B**), and marketable fruit number (**C**). Each value represents the mean ± SE of three replicates. Bars with the same letters are not significantly different, as determined by Tukey's test ($p < 0.05$).

Conversely, under moderate deficit irrigation (75% WC), statistically significant differences among CW treatments became evident for total production (Figure 1A). In particular, the highest CW incorporation rate (37.5%) differed significantly from the two lowest CW percentages (0 and 6.25%) (2789 vs. 3432 (on average) g plant^{-1}). In contrast, low-to-moderate CW rates generally did not significantly differ from the non-amended control substrate in total fruit number and marketable fruit (on average 88.6 n plant^{-1} and 88.1 n plant^{-1}, respectively). (Figure 1B,C).

Under severe water deficit (50% WC), despite an overall reduction in yield components, no significant differences were observed among CW treatments (on average 2263 g plant^{-1}).

Overall, the absence of yield penalties at low-to-moderate citrus waste incorporation rates supports the suitability of this material as a component of coconut-coir-based substrates, whereas excessive amendment levels may adversely affect fruit production, particularly under intermediate water-limited conditions (75% WC).

3.3. Fruit Quality Parameters

With respect to the irrigation regime, significant differences were observed for most quality traits (Table 4). Lightness (L*) decreased under severe water deficit (50% WC), whereas fruits grown under 100% WC and 75% WC showed higher and comparable L* values.

Table 4. Fruit color parameters (L*: brightness; a*: green intensity, chroma component ranging from green (–60) to 673 red (+60); b*: chroma component ranging from blue (–60) to yellow (+60)), pH, Titratable acidity, Total Soluble Solid (TSS), and Maturity index in the tomato cv Proxy grown greenhouse under optimal (100% WC irrigation), medium water deficit irrigation (75% WC), and severe water deficit irrigation (50% WC), and different percentages of CW (0%, 6.25%, 12.5%, 25.0%, and 37.5%).

Treatments		L*	a*	b*	pH	Titratable Acidity (g CA 100 mL^{-1})	TSS (°Brix)	Maturity Index
Irrigation (I)	100% WC	41.8 ± 0.58 A	18.2 ± 0.52 B	9.42 ± 0.70 AB	4.0 ± 0.04	0.62 ± 0.02	6.11 ± 0.15 B	10.0 ± 0.31 B
	75% WC	42.0 ± 0.57 A	18.1 ± 0.63 B	8.53 ± 0.57 B	4.0 ± 0.02	0.62 ± 0.03	6.38 ± 0.17 A	10.6 ± 0.49 B
	50% WC	40.7 ± 0.51 B	20.3 ± 0.54 A	10.33 ± 0.54 A	4.1 ± 0.02	0.55 ± 0.02	6.39 ± 0.10 A	11.9 ± 0.45 A
Citrus Waste (CW)	0%	41.7 ± 0.79	17.9 ± 0.68 B	11.2 ± 0.54 A	4.2 ± 0.02	0.55 ± 0.02	6.00 ± 0.08 BC	11.0 ± 0.43
	6.25%	41.0 ± 0.55	18.1 ± 0.76 AB	7.63 ± 0.76 C	4.0 ± 0.00	0.53 ± 0.02	5.76 ± 0.11 C	11.2 ± 0.69
	12.5%	41.2 ± 0.45	18.7 ± 0.83 AB	9.41 ± 0.31 ABC	4.0 ± 0.03	0.56 ± 0.03	6.06 ± 0.12 B	11.1 ± 0.70
	25.0%	42.3 ± 0.83	19.2 ± 0.78 AB	8.69 ± 0.52 BC	4.1 ± 0.03	0.68 ± 0.04	6.69 ± 0.08 A	10.1 ± 0.60
	37.5%	41.1 ± 0.92	20.4 ± 0.79 A	10.26 ± 1.14 AB	4.0 ± 0.05	0.66 ± 0.03	6.94 ± 0.16 A	10.7 ± 0.57
Significance								
I		*	**	**	ns	ns	**	**
CW		ns	*	***	ns	ns	***	ns
I × *CW*		***	**	***	ns	ns	***	*

Values are mean ± SE. Asterisks indicate a significant effect of irrigation (I), citrus waste percentages (CW), and their interaction (I × CW) according to ANOVA. ns = not significant; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Different letters indicate significant differences based on Tukey's test ($p < 0.05$).

The red–green coordinate (a*) increased significantly under 50% WC, indicating a more intense red coloration compared to fruits grown under higher irrigation levels. Similarly, b* values were significantly higher under severe deficit irrigation, reflecting changes in the yellow–blue component of fruit colour. The pH value did not show any significant variation, nor did it show any titratable acidity. Total soluble solids and maturity index were significantly influenced by irrigation, with higher values generally observed under reduced water supply.

Citrus waste incorporation rate significantly affected some fruit quality parameters. While L* and maturity index were not significantly influenced by CW percentage, significant differences were observed for a*, b*, and total soluble solids. In particular, increasing CW percentages were associated with higher a* values, and the highest CW rate (37.5%) showed significantly higher redness compared to the control. The b* coordinate varied significantly among CW treatments, with lower values generally observed at low to intermediate CW percentages. Fruit pH and titratable acidity did not differ significantly among CW treatments. Total soluble solids were significantly influenced by both irrigation regime and CW percentage: reduced irrigation and the highest CW incorporation rates were associated

with higher soluble solids. In contrast, the maturity index was affected only by the CW incorporation rate, with the highest value observed at the greatest CW inclusion.

Significant irrigation × CW interactions were detected for colour parameters (L*, a*, b*) (Figure 2), total soluble solids, and maturity index (Figure 3), indicating that the effects of citrus waste incorporation on fruit quality traits depended on water availability. Accordingly, differences among CW treatments in fruit quality attributes were more evident under specific irrigation conditions rather than being consistent across all water regimes.

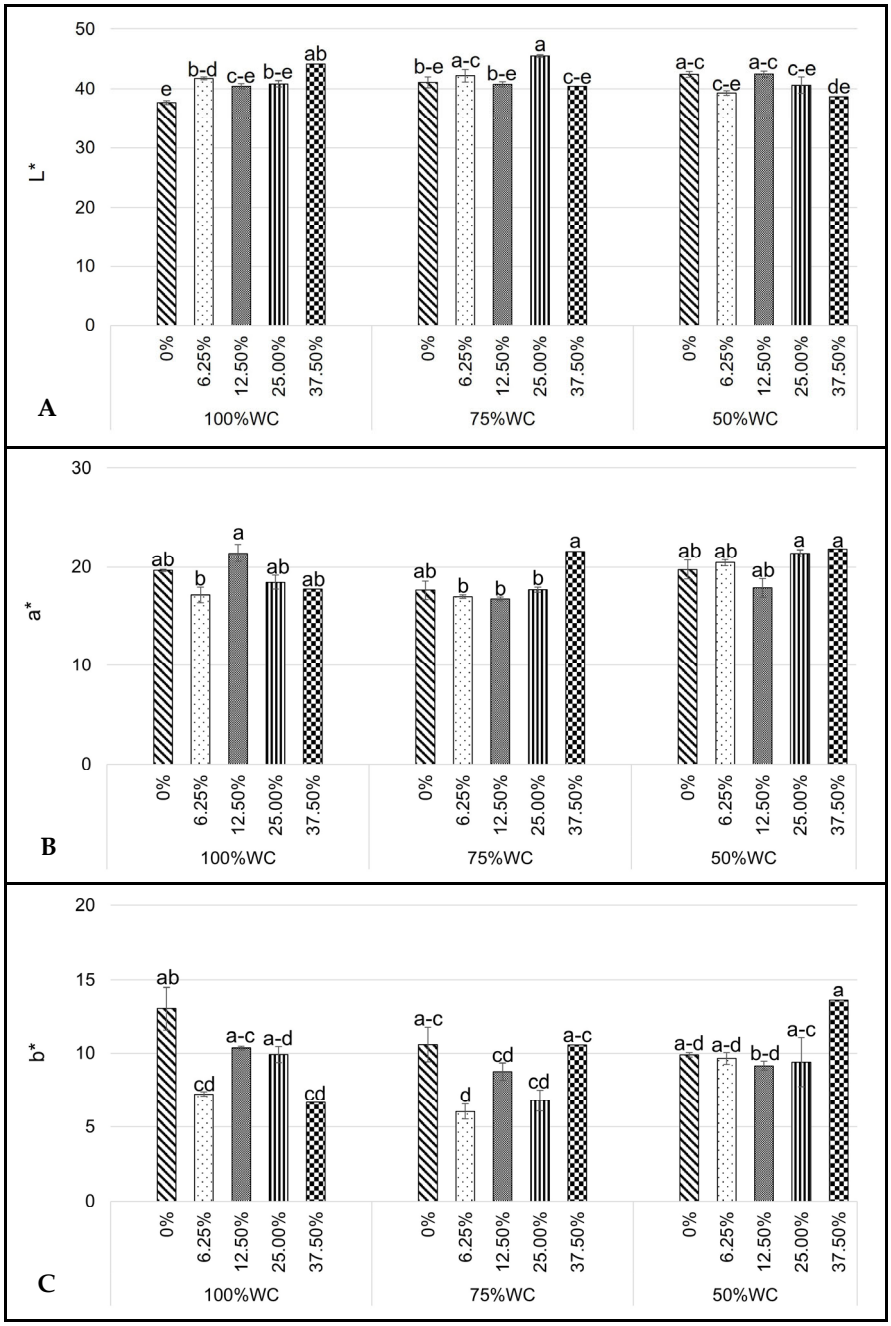

Figure 2. Interaction effects of water treatments at citrus waste percentages (CW) on brightness (L*) (**A**), a*: green intensity, chroma component ranging from green (–60) to red (+60) (**B**), b*: chroma component ranging from blue (–60) to yellow (+60) (**C**). Each value represents the mean ± SE of three replicates. Bars with the same letters are not significantly different, as determined by Tukey's test ($p < 0.05$).

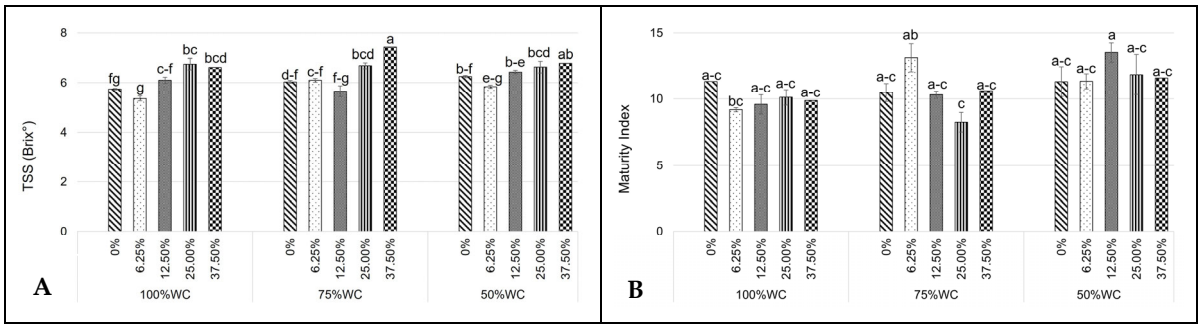

Figure 3. Interaction effects of water treatments and citrus waste percentages (CW) on Total Soluble Solids (°Brix) (**A**) and Maturity Index (**B**). Each value represents the mean ± SE of three replicates. Bars with the same letters are not significantly different, as determined by Tukey's test ($p < 0.05$).

4. Discussion

The development of sustainable growing media for soilless horticulture is a priority to reduce reliance on imported substrates and to advance circular-economy strategies. In this study, citrus-derived waste was evaluated as a locally available component to partially replace coconut coir under contrasting irrigation regimes. This rationale is consistent with the broader effort to substitute imported coconut fiber/coir with locally available organic substrates in arid and semi-arid contexts, where substrate choice can meaningfully affect plant water relations and physiological performance [18]. Progressive reductions in irrigation supply were associated with lower marketable fruit and fruit number, indicating that water availability remains a major determinant of crop productivity [21]. Under water-limited conditions, the influence of substrate composition on crop performance may be expressed as a partial agronomic (functional) buffering effect rather than full compensation of water stress [7]; the mechanisms underlying such functional buffering were not directly investigated in the present study. In line with this "functional buffering rather than compensating" framework, recent work on substrate blending with food-waste compost indicates strong sensitivity to blend ratio: intermediate compost proportions ($\leq$~50% v/v) can support robust early growth in tomato and watermelon, whereas higher compost fractions and compost-only media can reduce emergence and introduce substantial constraints relative to commercial mixes [17].

Within this context, the most relevant outcome concerning citrus waste (CW) is not simply whether it "increases yield", but whether it can be incorporated without agronomic penalties at realistic blending rates. Our results indicate that low-to-moderate CW incorporation (6.25–25.0% v/v) maintained production levels close to the unamended control; conversely, the highest inclusion rate (37.5% v/v) was associated with clear penalties in yield components. From an applied perspective, this provides a positive feasibility signal, suggesting that, at low-to-intermediate proportions, CW can serve as a local circular-economy matrix to partially replace conventional substrate components (coconut coir). Such blending strategies could reduce reliance on externally sourced materials while preserving productive performance. This interpretation is consistent with the general role attributed to organic amendments in improving water and nutrient buffering and supporting crop resilience under suboptimal water supply, as reported in the literature [15]. More broadly, it aligns with substrate research showing that performance neutrality at practical inclusion rates is itself an enabling outcome for adoption, because it delivers sustainability benefits without requiring yield gains [17].

The pattern observed at higher amendment rates, where yield and fruit number penalties become clearer, is consistent with the broader literature on composted or organic waste-based growing media: benefits are, in fact, strongly dose-dependent, and excessive

inclusion can reduce growth and yield. For instance, studies on compost use in container media demonstrated that relatively low compost proportions can be neutral or beneficial, whereas higher rates may depress performance depending on compost characteristics and crop sensitivity [16]. In the present study, a similar empirical, response-based "threshold effect" emerges from the yield data, supporting a practical recommendation: CW is best positioned as a blending component, rather than a dominant fraction of the substrate. This conclusion aligns with evidence that compost-rich substrates may be workable at moderate inclusion but can introduce constraints when compost proportions are high [17].

An additional and practically relevant key element emerging from the interaction plots is that the detectable differences among citrus waste incorporation rates were most evident under the intermediate water regime (75% WC), whereas differences tend to flatten under full irrigation (when water is less limited) and under severe deficit (when stress intensity may dominate plant response). This pattern suggests that under intermediate deficit, plants remain sufficiently productive for substrate-related differences to translate into measurable yield effects; conversely, under severe deficit, a "stress ceiling" may reduce the relative contribution of substrate variation. Conceptually, this is consistent with the view that amendments primarily provide functional buffering rather than overriding water limitation [15].

Fruit quality responses were broadly consistent with expected irrigation effects: reduced irrigation increased soluble solids and maturity index, while pH and titratable acidity were comparatively stable across different irrigation regimes and CW treatments. Changes in soluble solids under deficit irrigation may reflect concentration effects and altered source-sink relations; the direction observed here aligns with the wider literature on water limitation and tomato quality [15].

Importantly, the citrus waste literature supports the strategic value of routing citrus-processing residues toward agronomic uses. Citrus processing streams (solid residues and wastewaters) are characterized by high organic loads and variable composition, and their disposal can be environmentally and economically burdensome; shifting from conventional disposal to circular reuse is repeatedly identified as a priority pathway [8]. This is supported by the observation of Consoli et al. [7], who report that under field conditions, direct citrus-waste amendment improves soil-related indicators and can support more sustainable citrus production.

Although our system is soilless, it is conceptually and functionally aligned with field amendment approaches; the main differences relate to processing pathways and control requirements (e.g., pre-processing, solubility, and solution chemistry) rather than to the underlying reuse rationale.

From a value-chain perspective, CW reuse in horticultural substrates fits within the broader framework of "citrus by-products valorization", in which citrus residues serve as feedstocks for multiple endpoints (bioactive compounds, biomaterials, energy, and agronomic inputs). Reviews highlight that citrus peels and processing residues contain chemically valuable fractions (pectin, cellulose/hemicellulose, phenolics, essential oils), but their high biodegradability and variable composition can create pollution risks if unmanaged [3,10]. Building on this, CW reuse can support higher-value cascades, e.g., polyphenolic extracts and nanocellulose in a cascade biorefinery approach, generating both high-value products and residual fractions suitable for lower-value but high-volume outlets such as agronomic amendments [12,13].

In this context, substrate blending represents a high-volume valorization pathway that can absorb substantial quantities of local residues and improve the technical and economic feasibility of circularity in citrus processing. Its environmental value derives primarily from

reducing dependence on externally sourced substrate inputs and diverting waste streams from disposal routes [11].

This is also in agreement with studies on pelletized amendments derived from other industrial residues (e.g., sugar industry by-products), which show that waste-derived materials can enhance plant growth and soil properties when formulated and dosed appropriately [29]. Overall, the agronomic implications of the present results are twofold: (i) CW can be integrated at low–moderate rates with limited yield impact, supporting blending strategies; (ii) higher rates require caution and likely optimization to avoid productivity losses, particularly under moderate deficit conditions, where treatment differentiation is most evident.

5. Conclusions

This study evaluates the agronomic feasibility of incorporating citrus waste (CW), a common Mediterranean locally available by-product of the citrus processing industry, into coconut-coir-based substrates for soilless tomato cultivation under three irrigation regimes. Water availability remained the main determinant of tomato productivity, with reductions in yield and fruit number under deficit irrigation.

Across irrigation regimes, low to moderate CW incorporation rates (6.25–12.5%) caused only limited changes in yield components, with production values remaining close to those of the non-amended control substrate, whereas higher inclusion levels (25.0–37.5%) resulted in significant reductions in total production, while fruit number penalties were most evident at 37.5%. The irrigation × CW interaction indicated that treatment differentiation was most evident under moderate deficit irrigation (75% WC), while responses tended to converge under full irrigation and under severe water deficit.

Fruit quality traits were primarily driven by irrigation regime, with deficit irrigation generally increasing soluble solids and maturity index; citrus waste incorporation induced moderate, treatment-dependent changes in selected quality attributes without negatively affecting titratable acidity.

Overall, the results support the use of citrus waste as a substrate component at low-to-moderate proportions to partially replace imported coconut coir without marked penalties in tomato yield and fruit quality. Beyond agronomic performance, this practice offers a relevant environmental and economic opportunity by valorizing a local waste stream, reducing disposal pressures, and decreasing dependence on long-distance substrate supply chains, with potential benefits in cost and carbon footprint. Further research combining applied agronomic trials with substrate physical analyses and routine root-zone EC/pH monitoring is needed to elucidate the processes driving the yield and quality patterns observed under CW amendment and deficit irrigation.

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