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Assessment of Pistachio Shell-Based Biochar Application in the Sustainable Amendment of Soil and Its Performance in Enhancing Bell Pepper (*Capsicum annuum* L.) Growth

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Abstract: This study aimed to (a) analyze the influence of pyrolysis temperature on pistachio shell-based biochar (PSB) properties and (b) assess the PSB effect on green bell pepper (*Capsicum annuum* L.) growth. Pyrolysis experiments were conducted at different temperatures, determining 450 °C as optimal for soil amendment. The effect of PSB addition at different mass ratios was analyzed considering the physicochemical properties of the mixtures and the agronomic parameters of green bell pepper plants and fruits under greenhouse conditions. Results demonstrated enhancements in soil properties upon biochar incorporation, including a decrease in pH by 1%, a decrease in electrical conductivity (EC) by 4–14%, and increases in cation exchange capacity (CEC) by 4–8%, organic matter (OM) and organic carbon (OC) by 100–200%, and total nitrogen (TN) by 35%, relative to unamended soil. Agronomic variables revealed improvements, particularly during the reproductive and maturity stages, with plants treated with 1% biochar (SB1) exhibiting enhanced growth and chlorophyll content, alongside increased flower and fruit yields. Notably, the 2% biochar treatment (SB2) yielded superior fruit weight and length results, suggesting the potential for biochar to enhance both the quality and quantity of green bell pepper fruits, thereby contributing to sustainable agricultural practices.

Keywords: bio-waste; soil amendment; pyrolysis temperature; biochar; development of crops

1. Introduction

The increase in pistachio production has generated a greater amount of bio-waste (exocarp, branch fractions, stems, and leaves), generally removed with water, whose handling is often inadequate, resulting in various environmental issues, including water and soil contamination [1]. To address this situation, several governments have imposed legal restrictions on waste disposal, implying significant costs [2]. Therefore, pistachio shells must be used efficiently, as they are a valuable source of organic material that requires efficient processing and handling, contrasting with uncontrolled burning or accumulation. The integration of bio-waste transformation into biochar via the pyrolysis process, along with its application as a soil amendment, has the potential to fulfill the nutritional and structural requirements of soil in crop cultivation. This innovative strategy can reduce reliance on chemical fertilizers, enhance crop sustainability, and mitigate common challenges such as soil diseases and water stress [3]. An alternative to this bio-waste is to apply pistachio shells directly to the soil, although the benefits are limited because the decomposition rate is slow, which can lead to nutrient immobilization and hinder plant growth. This is because some studies suggest that direct application can improve soil quality and increase crop productivity, while others warn of possible risks to soil health and the creation of nutrient imbalances [4]. Despite this controversy, many agricultural systems continue to incorporate large amounts of unprocessed bio-waste into the soil in an attempt to maximize the use of available resources and reduce the amount of waste generated [5].

At the same time, the growing demand for healthier and more sustainable foods has spurred the search for fertilization alternatives, and the use of biofertilizer as a nutrient source for plants presents itself as a safe and environmentally friendly option [6]. In this context, biochar emerges as a resource of considerable potential, being the product of bio-waste pyrolysis under an inert atmosphere. Biochar generally has important mineral contents, making it a promising biofertilizer due to its positive influence on the germination, growth, and development of cultivations [7,8]. Its high CEC, porous structure, capacity for adsorption, and nutrient retention make it a promising soil amendment [6,9]. Also, it should be noted that biochar is remarkably resistant to degradation, which allows it to persist in soils and sediments over time [6].

Also, the conversion of bio-waste to biochar represents a potential solution to increase soil organic carbon content, improve soil quality, and address the problem of excessive waste management [10]. All these features show the opportunity to use biochar as a soil amendment to enhance cultivation performance (growth and yield) and production over extended periods [11–13]. However, it is crucial to consider that the effects of biochar on aspects such as plant growth and agricultural yield are often variable, depending on factors such as the raw material source, pyrolysis temperature, and application rates, among others [14,15]. Different feedstocks and pyrolysis conditions can alter the properties of biochar, affecting its ability to mitigate pollution and improve agricultural production. Modification methods, such as chemical treatments and H_2O_2 oxidation, are being explored to improve its effectiveness as a pollutant adsorbent [16]. Temperature is a key variable in this thermochemical process, significantly affecting the physicochemical characteristics of biochar [17]. Miri and Zamani Babgohari [17] observed that an increment in the temperature of pistachio pyrolysis, from 300 to 750 °C, produced a decrease in biochar yield and apparent density. The biochar obtained at 450 °C from pistachio improved soil drainage and plant availability. Also, a greenhouse study carried out by Jabborova et al. [18] showed that the addition of 2 and 3% of commercial biochar to the soil improved the lettuce yield, while Faria et al. [19] and De Lima et al. [20] found that the biochar obtained from poultry litter amendments promoted increased cultivation productivity. Sánchez et al. [21] added to soil 5, 10, and 15% of almond biochar and found that the lowest ratio of biochar presented better results in arugula seedlings.

Nevertheless, some studies have reported cases in which biochar addition to the soil had a neutral or negative effect on cultivation growth [22]. This variability could stem from differences in raw materials and production conditions, along with the diversity of plants and soils examined. Some studies indicate that biochar could have detrimental effects, as there is a possibility that it alters nutrient availability or modifies soil structure growth [22]. On the other hand, other researchers highlight its benefits in correcting the chemical properties of the soil, although they remarked that their results in terms of plant growth are not very promising [23].

The green bell pepper, a vegetable native to South and Central America, has emerged as one of the three most grown commercial vegetables globally. Its popularity stands out in Turkey, where its consumption reaches remarkably high levels [24]. Its presence in the food industry, either as fresh or processed fruit (dried or canned), underlines its economic relevance [25]. However, achieving quality production and high yields in the cultivation of *C. annuum* is a constant challenge [9,23,26]. In this context, the addition of biochar as a soil amendment emerges as an attractive possibility to enhance both the yield and quality of green bell peppers. Nevertheless, it is vital to emphasize that despite the growing trend of biochar use in modern agriculture, its agronomic value and crop-specific benefits still lack precise quantification.

Because green bell peppers are among the most widely consumed vegetables worldwide [9,23], and biochar use is intensifying in agriculture [6], the main objectives of this work were (a) firstly, to analyze the influence of pyrolysis temperature on the key properties of PSB, and subsequently, (b) to assess the biochar effect at the optimal pyrolysis temperature on the growth of green bell pepper. Therefore, pyrolysis tests were conducted at 450, 550, and 650 °C, and the biochar obtained was physicochemically characterized. Based on the values of the parameters analyzed on biochar and considering the characteristics of the soil to which it will be applied and the type of crop, the optimal pyrolysis temperature was selected. The effect of the PSB as a soil amendment was evaluated through the addition of biochar at different ratios (0%, 1%, and 2%, *w*/*w*). This study also assessed its impact on growth variables in green bell pepper plants under controlled greenhouse conditions. Also, the influence on fruit morphologic characteristics was analyzed.

Because biochar amendment has the potential to enhance soil fertility through nutritional enrichment and, consequently, to improve cultivation yield, this research aims to contribute to the understanding of the use of biochar to optimize agricultural production and soil quality in the context of environmental and food sustainability. PSB significantly improves the growth and development of green bell pepper plants compared to soil without organic amendment. It increases plant height, fruit, and flower production, and improves fruit morphological quality. These results demonstrate that PSB is a promising substrate for the optimal growth of green bell pepper plants in terms both of biomass and fruit quality.

2. Materials and Methods

2.1. Biochar Preparation and Characterization

2.1.1. Properties of Bio-Waste

The pistachio shells used in this study were provided by Frutos del Sol S.A., a local agricultural company, located in 25 de Mayo Department, San Juan Province, Argentina. Bio-waste, such as branches and dried leaves accompanying the raw pistachio shells, was separated by hand. The bio-wastes and raw feedstock were stored in mesh bags in the dark at 20 °C for 30 days until analysis. The physicochemical properties of the pistachio shell samples were analyzed. EC and pH were determined in an aqueous extract using a sample: water ratio of 1:5, according to the method proposed by Zhang et al. [27]. The determination of the OM content was carried out according to the methodology described in the UNE-EN 13039 standard [28]. Once the OM content was known, OC was determined according to the protocol described by Schulte and Hopkins [29]. The Kjeldahl method was used to determine total nitrogen (TN) [30]. Moisture was determined using a moisture analyzer (OHAUS model MB35 HALOGEN, Parsippany, NJ, USA), and results were expressed as a percentage [30]. Ash and volatile matter (VM) contents were determined according to ASTM standards (ASTM D1102-84; ASTM E872-82) [31,32], and elemental analysis was performed using an elemental analyzer (AuroEA3000, Elementar Analysensysteme GmbH, Langenselbold, Germany). In addition, lipid (AOAC 920.39) [30], lignin (ANSI/ASTM D 1106-56) [33], cellulose (ANSI/ASTM D 1103-60) [34], and hemicellulose (calculated using the difference between the contents of holocellulose and cellulose) contents were determined. All analyses were carried out in triplicate.

2.1.2. Pyrolysis Experiments for Biochar Production

Before pyrolysis, the pistachio shells were ground and sieved to obtain a particle size of 1190–2380 µm for subsequent analysis. The slow pyrolysis experiments were carried out in a stainless steel reactor with an internal diameter of 5 cm and a height of 100 cm, with internal refractory walls to avoid heat losses [35]. These conditions were kept constant for all experiments. At the end of each pyrolysis test, the obtained PSB was collected.

The dried samples of pistachio shells were introduced to the reactor with a moisture of 5%. The energy to heat the reactor was supplied by an electrical resistance with a power of 2000 W. The thermochemical process was carried out under the following conditions: nitrogen as inert gas at a flow rate of 100 mL·min^{-1}, a residence time of 2 h, and temperatures of 450 °C, 550 °C, and 650 °C [36]. To evaluate only the temperature influence on the biochar characteristics, the pistachio shell was introduced into the reactor when it reached the desired temperature.

2.1.3. Physical and Chemical Properties of the Biochar

The pH, EC, OM, OC, TN, proximate, and elemental analysis were determined following the procedures described in Section 2.1.1. The water holding capacity (WHC) of the biochar was determined according to Wu et al. [37], using glass funnels with filter paper (15 cm in diameter) and weighing the soil (50 g) in each funnel. A small segment of tubing was attached to the funnel and securely closed with a clamp. Water (50 mL) was slowly added to each funnel and allowed to stand for 30 min. After this, the clamp was released, and the water was allowed to drain from the funnel into a measuring cylinder for 30 min. The WHC of the soil was determined from the difference between the added water and the recovered water, deducting the amount of water retained in the filter paper. The CEC was determined by the saturation method with NH_4Ac at pH = 7 [38]. SEM-EDS analysis (carried out by the Laboratory for Analysis of Materials by X-ray Spectrometry, Cordoba University, Córdoba, Argentina) was realized to observe the microscopic structures of PSB and to identify different elements present in the biochar. The data were expressed as % by weight of the biomass weight of the dry and ash-free original raw material. A scanning electron microscope (SEM-EDS, EVO MA10W, Carl Zeiss, Jena, Germany) with a Bruker X-ray energy dispersion (EDS) microanalysis system (Quantax 200, Bruker, Billerica, MA, USA) and an SDD XFlash 6/30 analytical detector (Bruker, Billerica, MA, USA) were employed. Identification of the crystalline constituents was carried out primarily using X-ray powder diffraction (XRD).

2.2. Green Bell Pepper Cultivation

2.2.1. Study Area and Soil Sampling

This study was conducted in a greenhouse located on a farm in the town of Médano de Oro, Department of Rawson, Province of San Juan, Argentina (latitude 31.614011° S and longitude 68.511047° W) from February to June 2022. The experimental site is located at an elevation of approximately 605 m.a.s.l. The climate is desert, with annual rainfall not exceeding 150 mm, concentrated in the summer period. The average annual temperature is 17.8 °C, the average of the warmest month (January) is 26.3 °C, and the average of the coldest month (July) is 8.6 °C. It is characterized by a marked daily and annual thermal amplitude and frequent frosts during the winter season [39].

A simple random sampling design was used to obtain the initial soil sample. A zig-zag path was traced inside the greenhouse, covering a total area of 1200 m^2. The ten soil samples were collected at a depth of 15 to 30 cm, at which most root exploration activity and relevant biological processes are expected to occur. Each composite soil sample weighed approximately 1 kg. The samples were then air-dried and sieved using a 2 mm diameter sieve for subsequent laboratory analysis. The control soil was sampled at the beginning, before planting, and at the end of the crop cycle to evaluate changes in its physicochemical properties.

2.2.2. Physical and Chemical Characterization of the Soils

For the physical characterization of the soil, the following analyses were performed: texture, bulk density (BD), porosity, and soil color. The sedimentation volume method was used to determine soil texture according to Galantini et al. [40]. BD or bulk specific gravity is the ratio between the mass of the dry soil and the total volume of the soil, including the pore space. The units are g/cm^3 or t/m^3. The cylinder method was used to determine the

BD [38]. Porosity was calculated using the estimated bulk density and taking into account the real density, which is 2.65 g/cm^3 [41]. For the determination of soil color, the most common method was used, known as the Munsell scale tables. Soil should be determined under the following two conditions: dry and wet to saturation [42]. pH and EC were determined in saturated soil paste extract [43]. The CEC, WHC, moisture, OM, OC, and TN contents were evaluated according to the methods previously described in Section 2.1.3. In addition, soil respiration was determined using the method for estimating CO_2 during the incubation of soil in a closed system, in which CO_2 is trapped in a NaOH solution, which is then titrated with HCl [44]. All analyses were performed in triplicate.

2.2.3. Soil Preparation and Biochar Incorporation

Soil preparation included flood irrigation followed by fluffing and weeding. In addition, the soil was fertilized with horse manure at a rate of 10,000 kg/ha [45]. Subsequently, the beds were prepared for transplanting the final cultivation. The experimental design consisted of the following three treatments, differentiated by the PSB ratio (*w*/*w*) incorporated into the soil: SB0 (soil + 0% biochar equivalent to 0 ton·ha^{-1}), SB1 (soil + 1% biochar equivalent to 10 ton·ha^{-1}), and SB2 (soil + 2% biochar equivalent to 20 ton·ha^{-1}), each one with 25 plants. Because the PSB was concentrated in the planting area, doses were used, allowing for an appropriate distribution (1000 kg/ha).

To ensure the complete dispersion of the PSB across the planting site, precise dosages were meticulously administered (at a rate of 1000 kg/ha). The PSB, characterized by particle sizes between 2 and 5 mm, was uniformly integrated into the soil with a rake at depths ranging from 25 to 30 cm. After incorporating the biochar, the soil surface was leveled to create a smooth planting bed. Treatment plots were carefully delineated within furrows measuring 0.70 m in width and spaced at regular intervals of 1.20 m. Moreover, the greenhouse structure was strategically positioned with a west–east orientation, optimizing exposure to sunlight for enhanced plant growth and development.

The treatments were established in 0.70 m furrows with 1.20 m between them and the greenhouse was in a west–east orientation.

Subsequently, the control soil was characterized at the beginning of the crop, and then the selected biochar was added to the soil using different ratios (0, 1, and 2%, *w*/*w*, equivalent to 0, 10, and 20 t·ha^{-1}).

2.2.4. Transplanting

The green bell pepper seedlings of the Chango cultivar were obtained 50 days after germination with an average height of 6 cm and between 4 and 5 defined leaves. They were purchased from Fitotec S.R.L., located in RN40 km 149, Pocito Department, San Juan Province. Transplanting was carried out three days after soil preparation, in which the seedlings were placed manually using transplanting cones to facilitate the task. Planting was carried out according to a staggered frame with a planting distance of 30 cm.

The cultivation was watered with two irrigation belts per ridge at a frequency of 3–4 days throughout the cultivation cycle. Manual weeding was performed every 15 days. No pests or diseases were observed during the experiment, so it was not necessary to apply any type of insecticide. The crop was fertilized through direct injection into the irrigation system (fertigation) with a nitrogen product without the need for prior dilution. No pruning, thinning, or any other type of green work was carried out on the bell pepper cultivation during its development. Finally, the fruits of the cultivation were harvested 120 days after transplanting.

2.2.5. Physicochemical Characterization of Soil–Biochar Mixtures

Sampling of both doses was carried out at a depth of 25–30 cm at the end of the crop cycle to evaluate the physicochemical properties of the soil–biochar mixtures. Details regarding the techniques and calculations used to characterize these properties are described in Section 2.2.2.

2.2.6. Measurements of Agronomic Parameters during the Cultivation Cycle

Measurements of plant height and number of leaves were made on 10 randomly selected plants during the phenological stages of the crop (vegetative, reproductive, and ripening) for all treatments. Flowering plants and fruits were randomly counted for all treatments. In addition, the relative chlorophyll content (SPAD, index of chlorophyll content per unit leaf area) was determined with a portable chlorophyll meter (CM-B, Biobase, Jinan, China). Finally, at the end of the growing cycle, fruits were randomly harvested for each treatment, and images were taken and processed to analyze the main morphological characteristics of the fruits, including average weight (g), length (cm), width (cm), wall thickness (mm), and total yield of green bell pepper (ton/ha). The pH (AOAC 10.042), moisture content (AOAC 925.10) [30], acidity (AOAC 942.15) [30], and soluble solids (AOAC 923.12) [30] of the green bell pepper fruit were determined. The fruits evaluated were at the ripe green stage.

2.3. Experimental Design and Statistical Analysis

A three-level factorial design with three replicates each was used to characterize the soils and amendments. Means and standard deviations (SD) were reported. Data were analyzed using the two-way ANOVA model. Then, a post-ANOVA was performed to detect the significant differences between the levels of the different treatments using Duncan's test ($p < 0.05$) through software InfoStat 1.0 version (InfoStat Group, FCA, Universidad Nacional de Córdoba, Córdoba, Argentina, free academic license). Alternatively, the agronomic parameters were organized in a factorial design with three levels. The free software ImageJ 1.46 version [46] was used to analyze the agronomic parameters.

3. Results and Discussion

3.1. Characterization of Pistachio Shell

Table 1 shows the main characteristics of pistachio shell bio-waste, which were similar to the findings reported by Ibrahin et al. [47] and Jeníček et al. [48]. The pistachio shell has an acidic pH and a low presence of soluble salts due to the EC. The contents of OM and OC presented similar values to those reported by Ibrahim et al. [47] and Jeníček et al. [48].

Table 1. Chemical, proximate, and elemental analysis for pistachio shell.

	Pistachio Shell
pH	5.63 ± 0.24
EC (µS/cm)	335.33 ± 32.74
OM (%)	17.67 ± 0.42
OC (%)	10.25 ± 0.24
FC (%)	5.46 ± 0.64
Moisture (%)	4.91 ± 0.18
Ash (%)	0.33 ± 0.03
VM (%)	89.31 ± 0.52
C (%)	44.58 ± 0.18
H (%)	5.68 ± 0.01
O (%)	43.75 ± 0.04
Other elements (%) *	5.98 ± 0.18
Lignin (%)	27.02 ± 0.24
Cellulose (%)	74.56 ± 1.71
Hemicellulose (%)	10.33 ± 1.02

Electrical conductivity (EC); organic matter (OM); organic carbon (OC); volatile matter (VM); fixed carbon (FC); carbon (C); hydrogen (H); oxygen (O). * Other elements were calculated by difference.

The pistachio shells presented high values of O, C, VM, and H, while the ash content was similar to those reported by several authors [48–50]. The moisture and VM were consistent with the values informed by Kazimierski et al. [50]. These authors analyzed pyrolysis products from six agricultural wastes, including pistachio shells, walnut shells, sunflower shells, buckwheat shells, corn cobs, and coconut shells, to be used as a potential source of renewable energy. Hosseinzaei et al. [49] reported similar values of cellulose, hemicellulose, and lignin to those informed in this study for the same raw material.

3.2. Influence of Pyrolysis Temperature on Properties of Obtained Biochar

The pyrolysis process temperature is crucial for the biochar properties (Table 2). The proximate analysis showed a decreasing tendency in the VM content. Similar findings have been reported in previous studies [51–54]. VM represents a fraction that is likely to degrade with the increase in pyrolytic temperature due to thermochemical conversion, transforming pyrolytic volatiles into gases and low-molecular-weight organic compounds. The gases are released from biomass in the form of gas [55]. The devolatilization of the pistachio shell, the breaking of lower molecular weight hydrocarbons, and the increase in aromatization with the pyrolysis temperature are the underlying causes of the reduction in VM content. According to Dhar et al. [56] the low-temperature biochar is enriched in labile carbonyls, hydroxyl compounds, and oligosaccharides, influencing soil sorption capacity, plant growth, and nitrogen availability. Volatile components also control the surfaces and occupy the biochar micropores, being released at elevated temperatures and becoming available to ions [57].

Table 2. Characteristics of the PSB biochar obtained at different pyrolysis temperatures.

Properties	Pyrolysis Temperature (°C)		
	450	550	650
Moisture (%)	2.30 ± 0.18a	3.19 ± 0.04a	2.93 ± 0.01a
VM (%)	26.71 ± 1.11a	16.76 ± 0.56b	15.68 ± 0.96b
FC (%)	69.67 ± 1.23b	79.27 ± 0.59a	80.04 ± 1.00a
Ash (%)	1.31 ± 0.05a	1.09 ± 0.02a	1.03 ± 0.04a
C (%)	56.65 ± 2.36a	58.14 ± 0.22a	58.15 ± 0.11a
O (%)	36.24 ± 1.54a	34.84 ± 0.06a	34.59 ± 0.14a
H (%)	5.73 ± 0.04a	5.69 ± 0.00a	5.67 ± 0.01a
Other elements (%) *	1.03 ± 0.00a	1.27 ± 0.02a	0.80 ± 0.06a
TN (%)	0.32 ± 0.02b	0.35 ± 0.01b	0.51 ± 0.04a
pH	7.38 ± 0.21a	7.58 ± 0.43a	8.17 ± 0.12a
EC (µS/cm)	78.80 ± 7.13c	111.43 ± 10.08b	292.00 ± 18.58a
OM (%)	4.36 ± 0.09a	4.13 ± 0.14a	4.07 ± 0.40a
OC (%)	2.53 ± 0.05a	2.39 ± 0.08a	2.36 ± 0.02a
CEC (meq/100 g)	4.37 ± 0.57a	2.78 ± 0.00b	1.59 ± 0.00c
WHC (%)	2.76 ± 0.26a	2.44 ± 0.15a	2.61 ± 0.04a
Yield (%)	42.00 ± 0.12a	35.00 ± 0.08b	33.00 ± 0.23b

ANOVA. Values followed by different letters within the same row are significantly different, with $p < 0.05$. Volatile matter (VM); fixed carbon (FC); carbon content (C); oxygen content (O); hydrogen content (H); total nitrogen (TN); electrical conductivity (EC); organic matter (OM); organic carbon (OC); cation exchange capacity (CEC); water holding capacity (WHC). * Other elements were calculated using the difference.

A small decrease in the ash content with the pyrolysis temperature was observed, similar to those previously reported by Rodriguez Ortiz et al. [53] for walnut shells. The ash fraction is principally formed by minerals contained in the original feedstock, and they largely remain during pyrolysis, increasing their concentrations in biochar [58].

The FC content, representing the ash-free carbon fraction that remains after the release of VM, increases with the pyrolysis temperature. It has been revealed as a critical parameter for assessing the carbon sequestration capacity of biochar [53]. The FC content of PSB obtained at all temperatures was significantly higher than those reported by Rodriguez Ortiz et al. [53] for biochar from almonds and walnut shells; however, the found values were similar to those obtained by Schmidt et al. [54]. This aspect suggests that the PSB obtained at all temperatures had an efficient carbon retention. The high contents of cellulose and lignin, as well as the lignin-to-cellulose ratio in the feedstock, could be considered the cause of this high FC content. These fractions, being less disposed to release during carbonization, make a substantial contribution to carbon retention in the biochars. This carbon sequestration capacity may have significant implications for climate change mitigation and environmental sustainability enhancement, warranting further in-depth analysis in future studies [59].

The total C content in the biochar showed a slight increase with the pyrolysis temperature; however, no significant differences were found among temperatures. The total carbon percentage remained within a range of 56.1% to 58% at the highest temperature. Generally, the increase in C content with the pyrolysis temperature can be attributed to the formation of aromatic carbon structures and a higher carbonization rate [51,60]. This behavior could also result from the thermochemical breaking of C–H and C–C bonds, leading to the formation of stable aromatic hydrocarbons and improved removal of long-chain aliphatic members [60].

When the temperature increased (see Table 2), a decrease in the H and O contents of the biochar was observed due to the release of CO_2, CO, water, and hydrocarbons as gas [51,60]. This phenomenon is a characteristic behavior of the raw material during the pyrolysis process because at higher temperatures there is a structural degradation of the core, resulting in the release of O and H atoms bound to C [61]. Similar results have been observed by other authors [52,54,60–63]. The atomic O/C ratio has a remarkable influence on biochar stability because it is not completely inert when it is added to soil. The atomic O/C ratios obtained were 0.64, 0.59, and 0.60 for the PSB obtained at 450, 550, and 650 °C, respectively. Ippolito et al. [64] suggested that atomic O/C ratios in the range of 0.2–0.6 have half-lives between 100 and 1000 years. The atomic H/C ratio was 0.10 for the PSB obtained at all pyrolysis temperatures. According to EBC guidelines, the biochar obtained at all pyrolysis temperatures is stable because the H/C and O/C ratios are lower than 0.7 and 0.4, respectively [65].

The TN content slowly increased with the pyrolysis temperature. This phenomenon can be attributed to the presence of recalcitrant nitrogen in the raw material, whose release was influenced by the pyrolysis conditions. Similar findings have been previously reported by [53,54,60]. However, it is crucial to emphasize the need for thorough monitoring in the application of biochar in the context of agricultural management, especially in arid soils characterized by extended periods of drought. These conditions can exacerbate the accumulation of salts on the soil surface, which, in turn, could contribute to soil salinization. This aspect underscores the importance of considering the specific implications of biochar use in different environments and highlights the necessity of appropriate management strategies to maximize its benefits without incurring undesirable secondary effects on soil and the agricultural ecosystem.

A low decrease in the percentages of OM and OC was observed, increasing the pyrolysis temperature. This phenomenon is primarily attributed to the pyrolysis process that occurs at higher temperatures, leading to the decomposition of OM present in the starting material. The OM and OC contents have a significant influence on agronomic applications because they are low in soil in arid climates [66]. Considering the vital role of biochar in fostering microbial activity, improving soil nutrient accessibility, augmenting water retention, and its potential for developing innovative biochar-based controlled-release fertilizers, the incorporation of OM and OC stands to yield substantial advantages [67].

As reported in Table 2, the increase in pyrolysis temperatures significantly elevated the pH values of the PSB. It is important to note that the PSB obtained at 650 °C presented an alkaline pH, which is in agreement with previous research [68]. These authors suggest that the pyrolysis temperature increase promoted the dissolution of carbonates and metallic oxides, resulting in a pH increase. The thermal decomposition of carbonates during pyrolysis releases carbon dioxide gas, which reacts with water to form carbonic acid. This acid initially increases acidity, but over time, it neutralizes other compounds, resulting in a higher pH in the biochar [68]. Moreover, pH increases are primarily attributed to the separation of alkali salts from organic materials with rising temperatures. At about 300 °C, alkali salts start to separate from the organic compounds, increasing the pH. In contrast, cellulose and hemicelluloses decompose at around 200–300 °C, yielding organic acids and phenolic substances that lower the pH. This parameter stabilizes around 600 °C, when all alkali salts are fully released from the solid structure [69]. Furthermore, the loss of acidic functional groups and the appearance of basic functional groups increase with the pyrolysis temperature [70]. In line with the results available in the literature, the pH of PSB increased with the pyrolysis temperature, although the ash content of PSB did not change significantly [58,60,71]. This may be attributed to its ash composition with low alkali salt contents. These pH variations could be controlled through the rates of PSB application to the soil. Soil neutralization through biochar addition has been shown to enhance the productivity of crop soils [53].

The increase in pH with pyrolysis temperature is not accompanied by a significant increase in ash content. This can be attributed to an increase in alkaline functional groups on the surface, as reflected in the EDS analysis, in which alkali and alkaline earth metals associated with the biochar are observed. Other mechanisms could also contribute to this phenomenon. For instance, the thermal decomposition of organic components present in the raw material during pyrolysis may release gases such as carbon dioxide and methane, which can increase the pH of the biochar by reducing the concentration of organic acids and carboxylic acids [60]. Various authors [53,58,60,63] reported similar pH trends considering the biochar obtained from other feedstocks, and Miri and Zamani [17] observed similar trends considering the biochar obtained from pistachio shell biochar. The PSB obtained at 650 °C could be used in the remediation of acidic soils; however, high salinity, which is reflected in the EC value, may have a negative effect on plant growth and soil organic matter [17].

Table 2 illustrates the effect of temperature on the EC value. It can be seen that there is a notable increase in EC values as a result of the pyrolysis temperature rise. This is primarily due to the increase in the content of soluble salts.

This phenomenon can be attributed to the VM loss, resulting in a higher concentration of elements (Ca, Na, and K) in the ash fraction. Furthermore, at lower pyrolysis temperatures, there may be a higher presence of soluble salts in the PSB, contributing to a lower EC [51,61]. Various authors [53,60,63] reported similar results considering biochar obtained from other feedstocks. EC evaluates the content of soluble salts in a biochar solution, and it reflects its fertilizer capability. High rates of PSB addition to soil could unfavorably disturb salt-sensitive plants, producing water stress, salt stress, and nutrient disproportions [72].

EC values of PSB increased with pyrolysis temperature, but all EC values were smaller than 4000 μS/cm (EC of saline soil $\geq$ 4000 μS/cm) [73], indicating that the application of PSB has no adverse effect on soil salinity.

The CEC is the total ability of a biochar to adsorb and exchange positively charged species [74]. CEC is a function of the presence of oxygenated functional groups in the biochar and the material's surface. The CEC decreased with an increase in the pyrolysis temperature (Table 2), which has also been observed by other authors [57,75]. According to Yang et al. [75], it is attributed to the removal of surface functional groups and the formation of aromatic carbon. Banik et al. [76] reported that the CEC of biochar depends on the nature and distribution of oxygen-containing functional groups on the biochar surface. Negative charge sites on biochar surfaces are attributed to carboxylate and phenolate functional groups [69].

WHC is an important parameter that measures a biochar's ability to retain water through adhesion and cohesive forces [74]. The WHC of the biochar ranged between 2.44 and 2.76% (Table 2). The biochar produced at 450 °C had the highest WHC; however, no significant differences were found between different pyrolysis temperatures. Several authors have reported a decrease in WHC with pyrolysis temperature [58,60]. The WHC of soil is primarily determined by its texture and organic matter content. For sandy loam, loam, and clayey soils, typical values are 21%, 30%, and 38%, respectively [77]. Water available for plants is stored in the soil's micro and mesopores. Biochar enhances soil WHC by increasing its porosity and pore continuity [75].

As the pyrolysis temperature increases, the biochar yield decreases (Table 2). This is primarily due to thermal decomposition, gasification, and secondary reactions [53]. One might expect that if volatile compounds decrease, the ash content should increase. However, pyrolysis processes are complex and can involve a variety of chemical and physical reactions that may influence the composition of the resulting biochar. For instance, at high temperatures, some organic components may undergo more complete decomposition and secondary reactions that could lead to the formation of additional volatile products, as well as the release of certain inorganic components that were originally present in the feedstock in the ash form [78].

The microscopic structure of biochar is crucial for its effects on the soil. During pyrolysis, its surface area significantly increases, enhancing water retention. This structure is also associated with its capacity to retain nutrients and its influence on soil, minerals, and microorganisms [79]. Analysis using scanning electron microscopy (SEM) reveals changes in the PSB surface considering the temperature influence. At higher temperatures, the surface becomes rougher and reticulated, potentially facilitating nutrient adsorption and microbial colonization (Figure 1). A more tightly packed structure was observed at a temperature of 450 °C. In addition, it shows some macropores and cracks at its surface. Otherwise, at 550 °C, the morphology becomes smoother, with collapses and micropores, leading to structural degradation [80]. At 650 °C, pores begin to develop again, but macropores decrease due to the presence of condensed aromatic structures [80,81].

Through the pyrolysis temperature increase, the pores can expand and join during the decomposition of the hemicellulose, cellulose, and lignin contents, weakening the walls of the pores and decreasing their number [71].

The EDS analysis exhibits the elements found on the surface of the samples (Figure 1). The upper graphs present total elements, while those below indicate the presence of lower proportion elements after de-estimating C and O. Naturally, the bio-waste contained a lower percentage of C (51.3% wt) compared to the PSB (>81.9% wt) and a higher percentage of O (45% wt vs. <12% wt). These results were similar to those shown in Table 1. Considering the microelements, it is observed that the PSB obtained at all pyrolysis temperatures contains Ca, Mg, K, Fe, and Na.

The crystalline structures of both, raw pistachio shells and PSB obtained at different temperatures, were determined through X-ray diffraction. The XRD patterns of the pistachio shell and its biochar are shown in Figure 2. The diffraction peaks of the raw pistachio shells (Figure 2a) exhibited in the range of 2θ between 15.0 and 25.0° indicated the presence of cellulose, hemicellulose, and lignin as major components, which coincides with the values obtained (Table 1) and reported by Gholami and Mousavinia [82] for the same bio-waste. Different peaks observed in the case of PS were less prominent compared with PSB obtained at different temperatures (Figure 2b), indicating a less ordered, amorphous crystalline structure. The characteristic peaks of the carbon structure are also observed in previous works [83] because they tend to increase with pyrolysis temperature by crystallization [51], and this is associated with the formation of fixed carbon and the reduction of volatile carbon.

Considering these findings, selecting PSB obtained at different pyrolysis temperatures for agricultural biochar production will depend on specific soil conditions and crop types. In this study, the OM and OC contents, low EC, and neutral pH were prioritized because the PSB will be applied to soil in arid regions. It also maintains higher levels of CEC and WHC. Based on these findings, the choice of PSB obtained at different pyrolysis temperatures for agricultural biochar production will hinge on the particular soil conditions and crop varieties. In this investigation, emphasis was placed on OM and OC contents, along with low EC and neutral pH, given the application of PSB to arid soil. Additionally, PSB exhibits elevated levels of CEC and WHC. At 450 °C, the OM degradation was notably minimized, ensuring a significant portion was retained in the PSB. This preservation enhances its capacity to retain nutrients and water, thereby benefiting both soil health and plant growth.

Moreover, an optimal equilibrium was attained between OM retention and the formation of stable OC, which is very important for the long-term resilience of biochar in the soil.

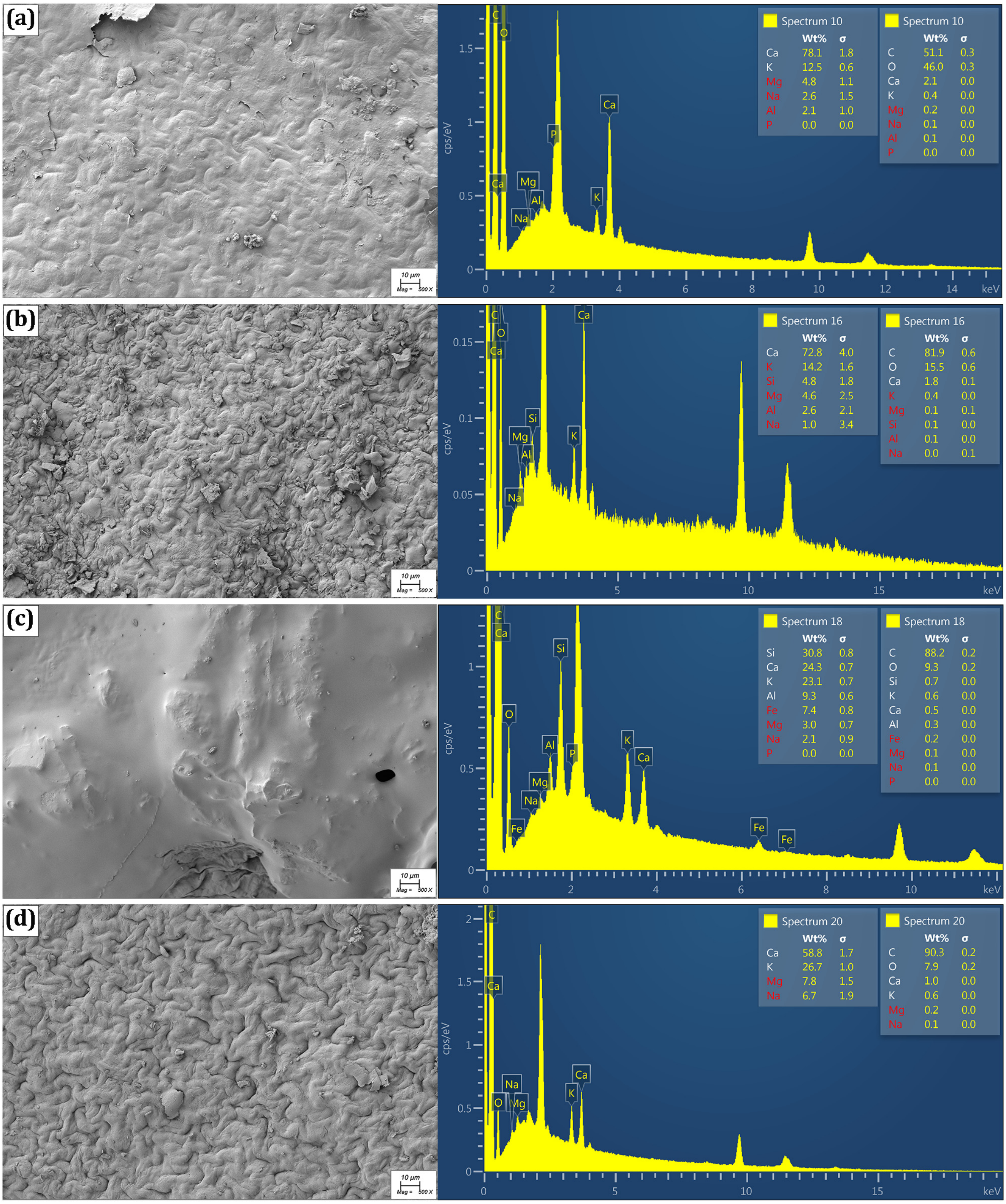

Figure 1. SEM micrograph (500× magnification) and EDS spectrum of pistachio shells (PS) (**a**) and pistachio shell biochar (PSB) at 450 °C (**b**); 550 °C (**c**) and 650 °C (**d**). Elements in red mean a lower certainty of presence in the sample.

Furthermore, previous studies have demonstrated that biochar produced at 450 °C exhibits adequate water retention capacity and organic matter content, contributing to soil structure improvement and fertility enhancement [80], and may offer significant benefits for crop growth and soil health. Similarly, Liu et al. [84] found that biochar produced at 450 °C enhanced nutrient retention in soil and promoted the growth of maize plants. A temperature of 450 °C provides better results while reducing both energy consumption and production time (considering higher temperatures), leading to a notable decrease in cost. In summary, a temperature of 450 °C could be considered the most suitable and economically viable option for the production of agricultural biochar.

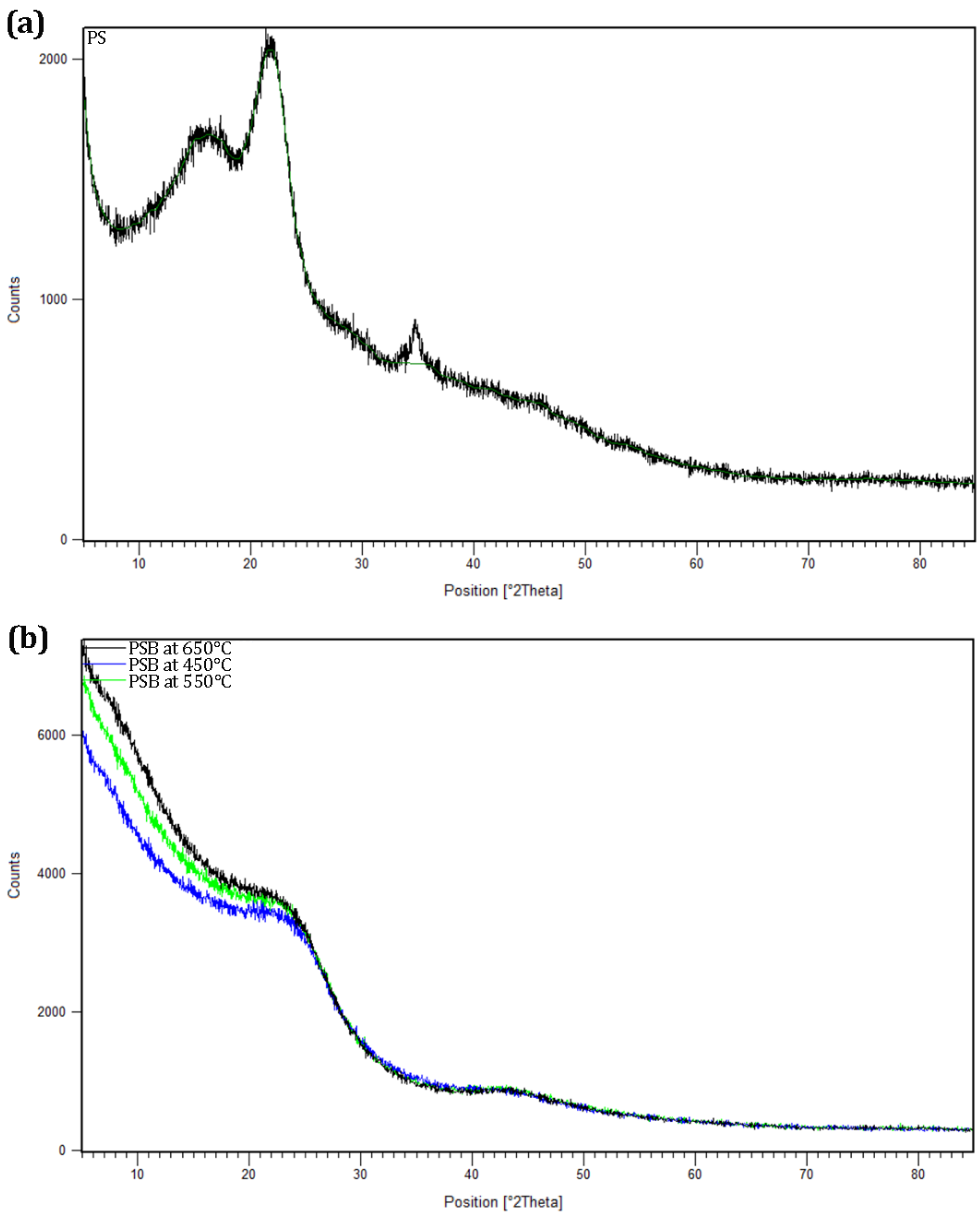

Figure 2. XRD of pistachio shell (PS) (**a**) and pistachio shell biochar (PSB) at 450, 550, and 650 °C (**b**).

3.3. Physicochemical Characterization of the Study Soil and Its Mixtures with Biochar

Table 3 shows the main physicochemical characteristics of the studied soil and their corresponding mixtures with PSB at the end of the crop cycle. It is important to note that because no differences were detected in the control soil at both the beginning and end of the crop cycle, it was decided to present only the results of the soil analysis at the end of the crop, along with the samples treated with different doses of biochar amendments.

Table 3. Values of the variables studied in soil and their corresponding mixtures with PSB.

	SB0	SB1	SB2
pH	7.45 ± 0.05a	7.35 ± 0.03b	7.32 ± 0.04b
EC (µS/cm)	412.33 ± 9.29a	394.00 ± 18.36a	352.00 ± 21.43b
CEC (meq/100 g)	28.99 ± 1.12a	30.25 ± 0.01b	31.30 ± 0.81c
OM (%)	1.47 ± 0.06a	3.13 ± 0.46b	4.45 ± 0.15c
OC (%)	0.85 ± 0.03a	1.66 ± 0.06b	2.58 ± 0.09c
TN (%)	0.25 ± 0.02a	0.17 ± 0.03a	0.16 ± 0.04a
Moisture (%)	19.47 ± 0.23a	19.75 ± 0.19b	21.51 ± 0.13c
Ash (%)	4.39 ± 0.09a	4.23 ± 0.49a	3.94 ± 0.14a
Texture (mL%/g)	131.67 ± 1.53a	133.67 ± 1.53a	138.33 ± 1.53b
BD (g/m^3)	1.02 ± 0.08a	0.93 ± 0.04a	1.06 ± 0.02a
Porosity (%)	61.52 ± 3.20a	64.92 ± 1.60a	59.83 ± 0.80a
Respiration (mg CO_2)	9.57 ± 1.03a	10.56 ± 0.94a	16.75 ± 0.06b
Color	10YR VALUE 4/CHROMA/4	10YR VALUE 3/CHROMA/4	10YR VALUE 3/CHROMA/3
WHC (%)	6.17 ± 1.42a	9.36 ± 0.13b	14.14 ± 0.70c

ANOVA. Values with different letters indicate significant differences between samples (Duncan's test, $p < 0.05$). Electrical conductivity (EC); cation exchange capacity (CEC); organic matter (OM); organic carbon (OC); total nitrogen (TN); bulk density (BD); water holding capacity (WHC).

The pH and EC values showed significant differences between soil samples, with a decrease occurring with increasing PSB amendment. Regarding the OM and OC contents, the SB2 treatment showed significantly higher values than SB1 and SB0. These results are in agreement with those informed by Zhang et al. [85]. They found a decrease in OM and OC contents with an increase in soil pH and EC values. In contrast, no significant differences were found for TN values among treatments.

The CEC values increase with the addition of biochar; this is mainly due to the ability of biochar to adsorb cations that are essential nutrients for plants [9,86]. On the other hand, the average CEC values are in the same range of clay soil texture according to USDA [87]. The results obtained showed statistical differences in soil texture, with SB2 being the most acceptable treatment compared to the control and the lower biochar treatment (SB1). However, it is important to note that the three soil samples were classified as a silty clay loam soil type. Moreover, soil texture plays an important role in influencing various factors, such as water retention, nutrient availability, and root development. These factors can influence plant growth and productivity. Therefore, it is imperative to consider soil texture when determining the optimal dosage of biochar or any other soil amendment. This ensures that the amendment complements the existing soil characteristics and promotes overall crop health and yield. BD and porosity did not show significant differences between treatments. Soil respiration, measured by CO_2 estimation, showed a high level for treatment SB2, indicating a microbial improvement in the soil with the addition of higher doses of biochar [75].

For the WHC variable, significant differences were found for all treatments, producing an increase in those with biochar content compared to the control. The SB2 treatment presented higher soil water retention. Sarker et al. [88] reported that the addition of biochar (BC) was the most influential factor in the absorption of the two pesticides studied, as well as their WHC, especially at a concentration of 1% BC, which showed the best results.

Slight differences in soil color were observed for the different treatments, varying the different visual color attributes, including hue, value, and chroma. In all cases, the colors indicated that the soil was found to be in good to fair condition [89,90]. All the characteristics of the control soil were consistent with those reported for a Médano de Oro soil complex. The soils of this region are generally considered to be different from the rest of the province due to their darker color, low pH (between 5 and 7.2), high OM content, and drainage problems (revenition) [91].

3.4. Agronomic Parameters during the Cultivation Cycle

The plant height variable did not show significant differences during the vegetative period (Stage 1) (Figure 3a). On the contrary, during the reproductive period (Stage 2), significant differences were found, with greater plant height in the treatment with the highest PSB ratio (SB2). In the maturity stage (Stage 3), significant differences were observed between the PSB treatments (SB1 and SB2) and the control, but no differences were found between the different ratios.

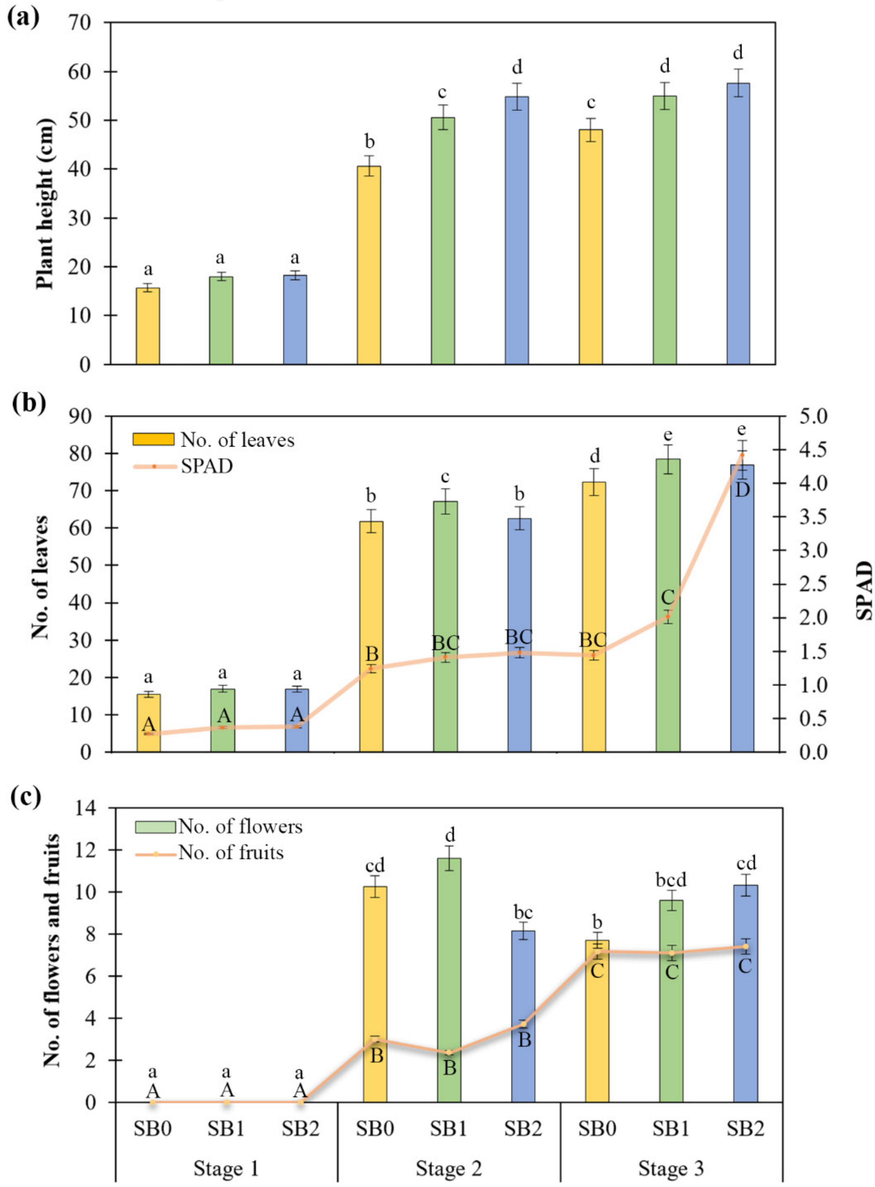

Figure 3. Development of plant height (cm); (**a**) number of leaves per plant and chlorophyll content (SPAD); (**b**) number of flowers and fruits (**c**) at different phenological stages of the cultivation for each treatment, including soil + 0% biochar (SB0—yellow bar), soil + 1% biochar (SB1—green bar), and soil + 2% biochar (SB2—blue bar). Data are expressed as mean ± standard deviation (n = 20). Significant differences between treatments and stages were indicated using different lowercase and uppercase letters (Duncan's ANOVA, $p < 0.05$).

Significant differences were found during Stages 2 and 3 in the number of leaves and their chlorophyll content (SPAD) (Figure 3b). During the reproductive stage (Stage 2), it was observed that plants corresponding to SB1 had a greater number of leaves than the control. However, chlorophyll content was not affected by the PSB ratio compared to the control. On the other hand, during the maturity stage, the plant biomass did not show significant differences between SB1 and SB2, but it did with SB0. In addition, chlorophyll content (SPAD) increased significantly with increasing PSB content (SB2). Jaaf et al. [92] evaluated the effect of corncob biochar on red bell pepper growth, finding that biochar had a variable effect on plant growth parameters such as height and number of leaves per plant, while biochar in combination with poultry litter resulted in better results, concluding that biochar should be applied together with another mineral or organic material source.

Figure 3c shows that the presence of flowers and fruits was evident between the reproductive and ripening stages, with significant differences in the number of flowers for the different treatments. In both stages, the green bell pepper plants treated with 1% biochar (SB1) showed a greater development of flowers compared to the other treatments. There were no significant differences in the number of fruits among the treatments, with a greater number of fruits at Stage 3.

During Stage 2, the higher number of leaves and flowers per plant in samples treated with 1% biochar could be attributed to a specific physiological response to this lower biochar concentration. The 1% biochar likely promotes an optimal soil environment for plant development during this crucial reproductive phase. This lower concentration could provide the necessary nutrients in a balanced manner that would promote the formation of a greater number of reproductive structures such as leaves and flowers [93]. Biochar enhances plant growth by directly influencing root development through potential changes in soil quality. Additionally, it modifies the soil's ability to retain fertilizers. Other factors contributing to improving plant growth and yield with biochar include increased nitrogen use efficiency, greater cation exchange capacity, enhanced water retention, and increased mycorrhizal abundance [93,94].

On the other hand, in crops treated with 2% biochar and showing a lower number of leaves and flowers during the reproductive period, this higher concentration may generate some type of physiological stress in the plants. This stress could be related to nutrient saturation or an imbalance in the soil due to the high concentration of biochar, which may interfere with normal reproductive development processes. Previous studies have shown that excessive doses of biochar can adversely affect plant growth and development by altering the physical and chemical properties of the soil, as well as nutrient availability [95]. The addition of high concentrations of biochar may negatively affect soil microbes by potentially inhibiting biological nitrogen fixation. These adverse effects could hinder seed germination, suppress crop growth and development, and ultimately compromise yield performance [93].

3.5. Harvest: Morphological Fruit Characteristics

Figure 4 shows the green bell pepper fruits obtained in each treatment applied to the soil with PSB amendment.

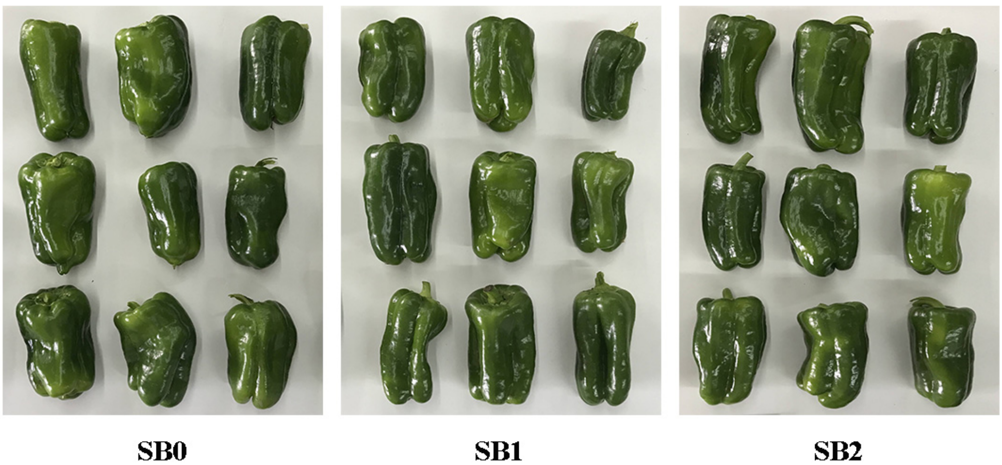

Figure 4. Green bell pepper fruits after harvest for each treatment (SB0, SB1, and SB2).

The physicochemical parameters of the analyzed fruits are summarized in Table 4. Considering the fruit weight, the SB2 treatment showed average higher values compared to the control and SB1 treatments. It was also observed that the fruits obtained from the SB2 treatment had a significantly greater length compared to the control (SB0) and SB1 treatments. No significant differences were found between the treatments for fruit width and wall thickness. Al-Harbi et al. [96] found an improvement in marketable yield and fruit quality of bell peppers when they combined intermediate doses (2%) of biochar with compost (2%) under two different irrigation systems when evaluating fruit length, width, and wall thickness. It is remarkable that in this work, the soil was fertilized with horse manure, a traditional practice in the region.

Table 4. Physicochemical parameters measured in fresh bell peppers for each treatment.

	Treatments		
	SB0	**SB1**	**SB2**
Average weight (g)	97.00 ± 17.27a	103.40 ± 17.71ab	110.53 ± 14.45b
Length (cm)	10.55 ± 1.14a	12.07 ± 1.27b	14.05 ± 1.17c
Width (cm)	5.83 ± 0.50a	6.23 ± 0.80a	6.16 ± 0.60a
Wall thickness (mm)	0.54 ± 0.14a	0.56 ± 0.11a	0.53 ± 0.07a
pH	6.16 ± 0.06a	6.20 ± 0.05ab	6.09 ± 0.03b
Acidity (g tartaric acid/100 g dwb)	0.07 ± 0.00a	0.06 ± 0.02a	0.09 ± 0.02a
Moisture content (%)	93.27 ± 0.13a	93.84 ± 0.54a	93.26 ± 0.20a
Soluble solids (°Brix)	5.00 ± 0.01a	5.00 ± 0.02a	5.00 ± 0.01a
Fruit yield (t/ha)	26.25 ± 0.18a	30.75 ± 0.23b	31.10 ± 0.16b

Significant differences between treatments are indicated by different lowercase letters (Duncan's ANOVA, $p < 0.05$). dwb = dry weight basis.

However, some studies indicate that the doses of biochar used as amendments may lack nutrients, which does not improve growth parameters in pepper fruits. Jaaf et al. [92] evaluated the effects of biochar from corn cobs and bird droppings on red pepper growth and soil properties. They discovered that bird droppings, whether used alone or combined with biochar at the same doses utilized in this study, enhanced soil quality, and promoted pepper growth. On the other hand, biochar application alone had a limited effect on plant growth because it did not provide enough nutrients for optimal plant development, suggesting its combination with mineral fertilizers or nutrient-rich organic materials. In a similar study, Tito et al. [23] investigated the effect of biochar produced from bird droppings on soil and pepper crops. They used different doses of biochar in the soil (0, 2.5, 5.0, 7.5, and 10 t ha^{-1}) and observed improvements in soil chemical properties and pepper growth. They recommended a dose of 5 t ha^{-1} to balance soil improvements without negatively affecting pepper fruit production.

Regarding the pH of the fresh samples, significant differences were found in all treatments, in contrast to the acidity, moisture, and soluble solids content, which did not show significant differences between treatments. Green bell peppers grown in SB0 showed similar values of pH and acidity and higher soluble solids value than those studied by Garuba et al. [97], who evaluated the effects of storage conditions and packaging.

The findings indicate that there are no significant differences in yields between treatments with 1% and 2% biochar. However, both treatments differ significantly from the control treatment. This suggests that the concentration of biochar may influence its effectiveness. With the SB2 treatment, a notable improvement in fruit production is found. These findings support the effectiveness of biochar in increasing pepper yields, even surpassing traditional fertilization methods [98,99].

Considering the findings of other researchers regarding the impact of various fertilizers on pepper crops, it is noteworthy to mention the study by Salma et al. [45]. In their research, they examined the effects of cow manure, poultry manure, and vermicompost, in combination with inorganic fertilizers, on the growth and yield of *C. annuum*. Their results revealed enhancements in pepper growth and yield, along with greater nutrient uptake compared to chemical fertilization alone. Vermicompost emerged as the most effective alternative for enhancing pepper production. Additionally, Poliquit et al. [100] explored the effects of fertigation on the soil chemical properties of peppers. They investigated various treatments, including water-soluble fertilizer, commercial controlled-release fertilizer, and fertirrigation in different ratios. Their findings demonstrated a significant improvement in soil characteristics such as pH, OM, nitrogen (N), phosphorus (P), and potassium (K) contents. Furthermore, they observed that nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) levels correlated with increased pepper yield.

4. Conclusions

Based on the findings of this study, it can be concluded that the treatment with pistachio shell-based biochar (SB2) proves to be highly beneficial for green bell pepper cultivation. An analysis of soil physicochemical properties revealed significant improvements in CEC and WHC with the addition of biochar, especially at a 2% dose. These enhancements in soil properties translated into a notable increase in plant height, number of flowers and fruits, as well as certain fruit quality parameters, such as weight and length.

Furthermore, during the crop maturity stage, a significant increase in plant biomass and chlorophyll content (SPAD) was observed in SB2-treated plants. These findings indicate that pistachio shell-based biochar can improve not only soil properties but also the growth and development of green bell pepper plants, potentially leading to an increase in crop yield and quality.

In summary, the utilization of pistachio shell-based biochar, particularly at a 2% dose (SB2), represents a promising strategy for enhancing sustainability and productivity in agricultural systems while efficiently utilizing agricultural waste. However, further studies are recommended to assess the long-term effects of this treatment and its feasibility under different soil and crop conditions. The use of this agro-industrial residue as an organic amendment offers both economic and environmental advantages by providing a sustainable alternative for its use. Consequently, this study highlights the relevance of using biochar in agriculture as a strategy to improve cultivation productivity and contribute to the sustainable management of agricultural resources. Nevertheless, a more extensive application to different agronomic conditions is still required to further improve the corresponding profit and contribute to agricultural sustainability.

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Nomenclature

C	Carbon content, (%)
CEC	Cation exchange capacity, (mmol/Kg)
EC	Electrical conductivity, (µS/cm)
EDS	Energy dispersive X-ray spectroscopy
FC	Fixed carbon content, (%)
H	Hydrogen content, (%)
M	Moisture, (%)
TN	Total nitrogen, (%)
O	Oxygen content, (%)
SD	Standard deviation
SEM	Scanning electron microscopy
VM	Volatile matter, (%)
WHC	Water holding capacity, (%)
PS	Pistachio shell
PSB	Pistachio shell biochar
SB0	Soil + 0% biochar
SB1	Soil + 1% biochar
SB2	Soil + 2% biochar

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