Characterization and Use of a Crop-Residue-Based Mat Mulch in the Production of Pepper (*Capsicum annuum*) during Dry Season

Víctor Hernández-Aranda 1,*, Diego Rojas-Tortolero 2, José Álvarez-Barreto 3, Carlos Arias-Vega 1, Jaime Proaño-Saraguro 4, Alexandra Portalanza-Chavarria 5 and Daynet Sosa 1,4

Abstract: Agricultural mulches from plant waste constitute an ecological alternative due to their capacity to biodegrade and incorporate into the soil. This work aimed at evaluating, during a drought, the effects of a mat mulch, based on banana rachis and rice straw, on bell pepper (*Capsicum annuum*) production, and to characterize the material, both mechanically (traction resistance) and physical-chemically (water retention capacity, organic and inorganic components). Two contrasting irrigation regimes were used to determine the effect of the mat mulch on edaphic and productive parameters such as plant height, basal stem diameter, number of fruits and flowers, harvest, plant biomass, macro- and micronutrients in leaves, weeds/m², and soil temperature. Treatments with the mat mulch resulted in increased height, number of fruits and flowers, biomass, and P, Zn and Cu concentrations. The mat mulch contributes to soil water retention, improves pepper agronomic variables response in plant’s height, basal stem diameter, and the number of flowers and fruits, especially with a low water irrigation regime. Furthermore, a 95% reduction in weed/m², and soil temperature (18 °C) compared to air temperature (26.8 °C) was found. The characteristics of the waste-based mat mulch in soils offer new possibilities for environmentally friendly, efficient, and sustainable agricultural practices.

Keywords: mulching; temperature; degradation; weeds; pepper

1. Introduction

Mulches can be defined as covers that are applied on soils, mainly to counteract the effects of local climate, as well as other factors that affect crops, when they are implemented [1]. The use of soil mulching in agriculture, both synthetic and organic, has become a prevalent practice worldwide [2]. The development and application of plastic mulches in agriculture since the 50s revolutionized certain selected vegetable crops [3]. In agricultural systems with low productivity due to low soil fertility and limited water supply and nutrients, the use of mulches becomes an essential option because they increase production and improve soil structure [4,5].
There is a variety of synthetic mulching that allows the reduction of weed growth, optimizing water consumption, maintaining soil temperature, and increasing production, among other benefits [6]. However, its continuous use generates poorly degradable waste that ultimately results in adverse environmental effects [7], although the use of plastic mulches continues to be an alternative, especially for the horticultural sector. In 2018, around 360 million tons of plastic production were distributed mainly in Asia with a 51%, United States, Canada and Mexico 18%, Europe 17%, Africa 7%, Latin America 4% and 3% in the Commonwealth of Independent States [8]. Despite its environmental disadvantages, many farmers keep using this type of mulching due to its low cost, or, often, lack of available alternatives that are more environmentally friendly [9].

In contrast, organic mulches are produced from plant residues, having similar beneficial effects to those of their synthetic counterparts, i.e., weed control, maintenance of soil temperature and water consumption [10,11]. Additionally, the continuous use of organic mulches, even in the fallow period, increases soil moisture and promotes nitrogen (N) uptake in the plants, improving production [12]. In places where water is scarce or expensive supply for agriculture, the use of this type of material promises to be an efficient and ecological solution [13]. Organic mat mulches have been created from a wide array of lignocellulosic material, such as general green waste, sawdust [14], geotextile weed mat [15], banana leaves [16], banana pseudostem [17], and rice straw [18], among others.

These mulches have direct effects on soil properties. Particularly, rice straw-based mulching has been shown to improve microbial diversity and soil functionality of apple orchards, by altering soil organic composition [18]. Similarly, a banana stem mulch demonstrated potential to provide and maintain potassium levels to the soil [19]. However, organic mulches can also positively affect plant characteristics. Mulch mats made from banana leaves improved guava tree growth and yield, in comparison to a commercially used black polyethylene mulch, resulting also in enhanced fruit quality [20]. Moreover, a similar mulch material resulted in greater soil moisture and fruit retention in a litchi field [21]. Thus, different organic mulches can be of great aid in providing means of combating climate change from agricultural practices.

Iriany et al. [17], proposed a composite rice straw-banana pseudostem mat to help plants adapt to climate change, which presented important physical and chemical properties, such as high tensile strength and sunlight intensity of mulch composition.

Banana rachis from *Musa cavendishii* has been studied for its components, such as holocellulose, alpha-cellulose, hemicelluloses, and K [22–24], and has been used into high value-added products. Similarly, rice straw has also been studied for its high cellulose and lignin content, and for its low biodegradation rate [25]. Based on their characteristics, both lignocellulosic sources can be used as a soil cover that will be incorporated into the soil through time.

On the other hand, pepper is considered an economically important vegetable crop often impaired by weeds. Management of weeds in pepper is required to minimize yield loss because this crop does not tolerate weed competition [26]. Therefore, the objective of the present study was to evaluate the mat mulch physical/chemical characteristics and its effects on a vegetable crop (bell pepper) during the dry season, under a controlled irrigation system (not dependent on rainfall).

### 2. Material and Methods

#### 2.1. Experimental Area, Soil Preparation, and Maintenance

The experiment was carried out in September 2016 at the Agricultural Experimental Farm located in the premises of Escuela Superior Politécnica del Litoral (ESPOL), campus “Gustavo Galindo”, Guayaquil, Ecuador (2°08′21.1" S, 79°57′46.1" W). The experimental plot’s selected zone had an area of 1250 m² in a clay loam soil (22% sand, 48% loam, and 30% clay) with a pH of 6.9. The assay’s climate conditions were: maximum temperature 35.8 °C, mean temperature 26.8 °C, minimum temperature 17.8 °C, relative humidity 71.5%, rainfall 11 mm, and global radiation 12.3 MJ/m²/day; daily data obtained from a weather
station near ESPOL owned by the National Institute of Meteorology and Hydrology of Ecuador [27].

For soil preparation, a brush cutter (HYBCF3, Hyundai, Taipei, TW) was used to eliminate most of the weeds on the terrain. A contact herbicide (Isopropilamine salt, Ranger 480, Ecuauquimica, Guayaquil, Ecuador) was applied to avoid competition with the crop. Seven days after the application, the soil was disk plowed; two passes (0.25 m depth) were made as a tillage method for penetrating and turning the soil, removing the remaining weeds, and loosening its surface layers; finally, twelve beds (1.5 m × 10 m × 0.20 m) were installed using a single bed maker, each one separated by a 0.20 m wide furrow.

A soil sampler tube (1016, LaMotte, Baltimore, MD, USA) was used to collect three composite samples, taken from the same plot, at a depth of 15 cm to determine the soil’s macro and micronutrient composition. At the end of the crop cycle, three more soil composite samples were taken in each bed (with and without mulch); holes of 0.03 m of diameter were made in the mulch, using the previously described soil sampler, again at 15 cm deep. K, Ca, Mg, Zn, Cu, Fe, Mn analyses were performed using atomic absorption spectroscopy, and P by colorimetric analysis (UV/Vis spectroscopy), using the modified [28] extraction.

Sweet bell pepper (Capsicum annuum L.) var. ‘Nathalie’ was used for the experiment. Seeds were sown manually, in black polystyrene germination trays, one seed in each alveolus. Germinating substrate (BM2, Berger, Saint-Modeste, QC, Canada) composed of peat, perlite, and vermiculite was used and kept under controlled conditions for 35 days at a temperature of 23 °C. In each bed, holes with an approximate diameter of 8 cm were made, and before the transplant, 50 gr/plant of organic fertilizer was applied. Then, 40 plants were placed manually in each plot, and a total of 480 seedlings were transplanted in the experimental area, using triangular sowing. Planting distance was 0.4 m between plants and 1.2 m between beds. Pepper production time was 120 days. A drip irrigation system was installed to supply water consisting of a hose line (STREAMLINE-16125, Netafim, Tel Aviv, Israel) placed above the mat mulch for every row of plants, and its emitters were 0.40 m apart.

Two contrasting irrigation regimes (high and low) to determine the effect of the mat mulch on edaphic and productive parameters, were used with the following treatments: T1: no mulch + 251 mm of water; T2: with mulch + 251 mm of water; T3 no mulch + 129 mm of water; and T4: with mulch + 129 mm of water. The amount of applied water was calculated using the decision support software CROPWAT [29,30] developed by FAO, based on the reference evapotranspiration (ET0) [31,32] method. The program incorporates procedures for reference crop evapotranspiration and crop water requirements and allows the simulation of crop water use under various climate, crop, and soil conditions. The crop coefficient (Kc), which relates the reference evapotranspiration (ET0) to the maximum evapotranspiration (ETm), is 0.4 after transplant, 1.08 during the total coverage, and for fresh peppers 0.6, during harvest. The total amount of applied water throughout the crop cycle was 251 mm based on the 100% of the evapotranspiration calculated (ETc) by Cropwat with the Penman–Monteith Equation. One hundred and twenty-nine millimeters of applied water was chosen to assess the mulch’s effect under such conditions and was calculated with the CROPWAT software using 50% of the ETc obtained with the equation previously mentioned. Irrigation was planned with the following frequency to supply this amount of water: to reach 251 mm, it was irrigated two days per week, two hours a day, and, for 129 mm, two days a week, for one hour a day.

In the present study, a commercial mulch was assessed. The mat mulch was made of banana rachis fiber and rice straw, in a 70% and 30% proportion respectively, sewn together with a synthetic yarn, presented as rolls with dimensions of 1.50 m × 5 m in length and 3 cm in thickness (Biomanto, Industrial Packing Depot, Guayaquil, Ecuador). Those two natural materials were chosen for being considered agrowaste, and having no commercial use in Ecuador, beyond their mere utilization as composting materials, after harvest.
rolls were placed on top the beds according to its respective treatments (T2 and T4). At the end of the crop cycle, the mat mulch was not ploughed into the soil.

For assure experiment maintenance, the following activities were carried out after transplant: a commercial bioinsecticide (5 cc/L water), biofungicide (2 g/L water), and a biofertilizer (10 cc/L water) were applied weekly with a manual backpack pump directly to the plant. Moreover, diluted urea N 46% (4 g/L water) and diluted muriate of potash (4 g/L water) were applied weekly, and after 34 days of being transplanted respectively, with a manual backpack, pumped directly to the soil. Additional tasks, such as covering the plants with soil, cleaning the plots, and manual control of weeds, were performed.

2.2. Mechanical and Physical-Chemical Characterization of the Mulch

According to the mechanical characterization, tensile strength tests were carried out, according to the norm ASTM D882, at the Metrological and Materials Testing Laboratory (LEMAT) located at Escuela Superior Politécnica del Litoral (ESPOL). The mulch and nylon yarn (used for sewing) was assayed using two universal testing machines, both manufactured by Shimadzu (Japan): UH-600KNi and AG-IS 10KN (mulch), respectively.

The weight and cross-sectional area of the samples were previously recorded using a vernier caliper (M.12203 Vv4, Surtek, Mexico City, Mexico), analytical balance (PL3001-S, Mettler Toledo, Columbus, OH, USA), and a digital thickness gauge (700-118-20, Mitutoyo, Sakado, Japan). Analysis of the mat mulch composition percentage (banana rachis/rice straw) were not performed.

For this purpose, the joint tension of the fibers (banana and rice) and of the nylon yarn (used to hold the fiber) was measured. The mechanical capacity was determined in two moments: before and after 70 days of being installed. For each experimental condition, eight (8) samples were tested. Nevertheless, the analysis was only done in the direction of the fibers (axial).

The identification of the physical-chemical characteristics was the first step to establish the potential of this product and forecast the behavior it would have in an agricultural system. Mulch characterization was performed under controlled conditions. Thus, the physical-chemical tests were carried out on samples of fresh mulch, determining the following parameters: pH in ratio 1:10 (sample: H₂O) at 180 rpm per 20 min, percentage of humidity and total ash following the methodology described by [33], and bulk density according to ISO 9427:2003 [34].

The water retention capacity and the swelling under water saturation were determined under controlled conditions in a greenhouse located at premises of the Biotechnology Research Center of Ecuador of Escuela Superior Politécnica del Litoral, Guayaquil, Ecuador (2° 09′03.7″ S, 79° 57′13.1″ W), under a controlled temperature of 23 °C.

Water retention was determined following the methodology described by [35]. Briefly, a roll of the mulch was sectioned in rectangles of 43 × 27 cm². The rectangles were weighed with an analytical balance (B2002-S, Mettler-Toledo, Columbus, OH, USA), and their dry weight was recorded. Then, these rectangles were placed inside rectangular aluminum trays of 50 × 30 cm², which had small holes to facilitate the drainage of surplus water; after that, a liter of water was added in the following time intervals: 2, 4, 6, 8, 24, 30 and 48 h. In each interval, every rectangle was weighed.

For swelling tests, mulch was cut into 16 × 16 cm² squares, and the dry weight of each was recorded. Afterward, 5 L of water was added to aluminum trays with dimensions similar to those used for the moisture retention test. The rectangles were placed in the bins, leaving them submerged for 24 h, and after this time, their weight was measured.

Evaluation of the mulch’s inorganic and organic components was carried out before its use in the field (fresh). The inorganic components were determined by the following methods: For nitrogen (N) the Kjeldahl method was used [36], while for the rest of the elements phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), and sodium (Na), using the microwave acid digestion method/determination in ICP-OES Analysis (Inductively Coupled Plasma Optical Emis-
This data allowed to determine the main components of the fresh mulch as well as the potential contribution of nutrients towards the ground.

The organic components measured in the mulch were: total organic matter by Loss-on-ignition method (LOI) at 550 °C, cellulose as described by [37], and lignin content that was carried out following the standard TAPPI T 222 om-98 [38].

2.3. Agronomic and Edaphic Variables in the Pepper Crop

Throughout the experiment, some random variables were measured only once and others repeatedly, the latter being totaled at the end of the experimental cycle. The present study does not consider a formal analysis of the time series of variables measured repeatedly. Instead, a visual approach is preferred when those time series are discussed. Classical factorial analysis is preferred in all cases.

The following agronomic variables were recorded to evaluate the effect of mulching on pepper production under two irrigation regimes: plant height from the base of the plant to its apical meristem (measured weekly, from their transplantation to the beginning of the harvest cycle); the number of flowers and fruits produced per plant at 45, 51, 57 and 64 days post-transplant; pepper harvest at 64, 74, 99, 106, 119 days post-transplant (the performance variable was “average weight per plant” or “harvest/plant” for short).

At the end of the cultivation cycle, 20 plants per plot were selected and then the basal diameter was measured. Subsequently, to estimate biomass, those plants were collected, separating its leaves and stems, and placed in paper bags, then weighed and settled in a stove at 65 °C for 72 h to obtain their dry weight. Finally, the content of macro- and micro-elements (P, K, Ca, Mg, Zn, Cu, Fe, Mn) and N were quantified as previously explained.

The number of present weeds per square meter (w/m²) was counted using a 1 m × 1 m quadrant at 21, 35, and 56-days post-transplant, based on the development of the weeds under the assay’s climate conditions. This methodology was repeated in each bed three times, and the sites were selected randomly. Soil temperature was monitored at 28, 35, 42, 56, 63 days, and was measured randomly at three-bed sites, at 20 cm deep, using a spear-type thermometer (Ti.30, Wika, South Carolina, GA, USA).

2.4. Experimental Design and Statistical Analysis

The assay was carried out with a complete 2² factorial design, with two factors (irrigation dose and mat mulch use) and two levels for each one (251 and 129 mm of water, with and without mulch, respectively). The treatments (T1, T2, T3, T4) were a combination of factors and levels, and each one was replicated three times and located randomly in the field. The results are presented as the (average ± standard deviation).

The treatments were located randomly; each replicate occupying one of the twelve available beds. Analysis of variance (ANOVA) and Dunnett’s tests was performed by using the software package Minitab 18. The latter was used in soil’s ANOVA to create 95% confidence intervals for differences between the mean of each factor level and the mean of the initial soil samples. For all tests, a significance level α = 0.05 was fixed.

3. Results and Discussion

3.1. Mechanical Characteristics of the Mulch

Tensile strength is among the most relevant mechanical characteristics for this type of material, as it serves as a way to assess mulch damage due to external stresses [39]. In this sense, tensile tests were carried out on the fiber and the synthetic yarn, both fresh and degraded mulch. The fresh mulch showed an ultimate tensile strength of 0.236 ± 0.153 MPa. The variability in this parameter was high, with the standard deviation being 64.8% of the average. This is probably a consequence of important variations due to the nature of the fibers (pseudostem and rachis), and the mulch’s manufacturing process since the lack of homogeneity of the material was apparent. Nevertheless, it is important to point out that the tensile stress decreases significantly (p < 0.05), with a
value of 0.104 ± 0.036 MPa in the degraded mulch. The standard deviation decreased, representing this time 34.7% of the average. Additionally, the tensile strength of the yarn was between 800 and 1900 times higher than the fiber’s strength in fresh and degraded mulch, respectively. The mulch’s structure is maintained mainly by the synthetic yarn.

The ultimate tensile strength values of the proposed mulch in this work are significantly lower than those reported for commercially available polyethylene films, with a value of approximately 40 MPa. The synthetic material had superior mechanical properties after seven years of soil burial, with values of around 20 MPa [40]. It is, nonetheless, an indication of poor degradability of the commercial products, corroborating the environmental hazards they represent. Other organic waste-based materials, such as fennel-based mulching, also presented higher tensile strength values than the banana rachis-based counterparts proposed in this work, with values if up to 3 MPa. However, this material had to incorporate another biopolymer (Poly-vinyl alcohol) [41], which could hinder the product’s economic feasibility.

Iriany et al. [17], reported that mulches based on banana pseudostem and rice straw, in combination with water hyacinth, yielded significantly lower tensile strength values with maximums of 30 N/m², four orders of magnitude lower than the ones found here. Even though there is a different component in the mentioned previous work, and that the fabrication technique is different, those results are also an indication that the high strength of the mulch assessed in the present study is mainly due to the use of the synthetic yarn. The use of a biodegradable yarn could be considered to improve the product herein characterized. For example, rice straw fibers could reach up to 80 MPa in tensile strength [42], and if the banana pseudostem fiber were obtained, yarns of over 200 MPa in tensile strength could be obtained. Therefore, their use in mulch preparation could grant both biodegradability and high mechanical properties [43].

These tests had an important implication and offered a clear idea about the resistance of the product when it is installed in the field; these results guaranteed crop coverage and degradation homogeneity. However, at the end of the crop cycle, the presence of the nylon yarn could affect the acceptation of the mat mulch because it would generate additional costs to remove it from the ground.

3.2. Physical-Chemical Characteristics and Components of the Mulching

The fresh mulch was slightly alkaline at pH 7.37 ± 0.093. The moisture content was less than 10 wt%, indicating that the raw materials were dry at the time of the manufacturing process. The bulk density was 0.09 g cm⁻³. In contrast, after 70 days in the field, a decrease in pH 6.34 ± 0.074 was observed, which is indicative of the biological degradation of mulch’s organic constituents [44]. Similarly, the moisture content dropped to 7.95 ± 0.192%. A drastic reduction of 93% was observed in the bulk density, from 0.09 ± 0.20 to 0.006 ± 0.005 g cm⁻³, while the total ash content increased by 58% (Table 1). All these variations are considered indicative of decomposition processes, which would be advantageous for soil health and plant nutrition. It is a comparative advantage concerning to synthetic mulches, which do not incorporate nutrients or other beneficial effects. According to [45], mulching enhances microbial biomass activity, and water availability for soil microbes helps to retain soil moisture, prevents weed growth, and improves soil structure.

| Parameters              | Fresh       | Degraded    | Difference (%) |
|-------------------------|-------------|-------------|----------------|
| pH                      | 7.37 ± 0.11 | 6.34 ± 0.07 |                |
| Moisture (%)            | 8.61 ± 1.15 | 7.95 ± 0.19 | 7.67           |
| Ash contents (%)        | 23.40 ± 3.43| 36.93 ± 18.99| +57.82         |
| Bulk density (g cm⁻³)   | 0.09 ± 0.20 | 0.006 ± 0.005| 93.33          |

The inorganic components of the fresh mulch were contrasted with the degraded one to determine the potential contribution of nutrients to the soil as a result of its decompo-
sition and incorporation. Among the main components of the fresh mulch, K, Ca, P, and Mg\(^{2+}\) were found in concentrations higher than 1000 ppm (0.1%). It was observed that, in the degraded mulch, the concentration of P, K, and Ca decreased by 70, 10, and 95%, respectively, indicating a possible contribution of these elements to the soil, which benefits plant nutrition. The degraded mulch showed increases in Cu, Mn and Zn concentrations of 325, 173 and 143%, respectively, suggesting that these elements are constituents or are embedded in other slow-decomposing matter, and would take more than 70 days to degrade and enter the soil (see ash in Table 1).

In general, the weight percent organic matter content in the fresh mulch was 76.61 ± 3.43; meanwhile, cellulose was 32.15 ± 4.66, and lignin 32.67 ± 5.22 as shown in Table 2. These results suggest that the lignin percentage value increases due to the decreasing of the bulk density. Similar results were reported by [46] in black locust mulch; lignin content rose from 13.11% to 51.0% (buried) and 32.9% (surface). Alfalfa mulch rose from 6.67% to 31.4% (buried) and 47.7% (surface).

**Table 2.** Lignocellulosic components in the fresh and degraded mulch.

| Parameters (wt%) | Fresh                  | Degraded               |
|-----------------|------------------------|------------------------|
| Organic matter  | 76.61 ± 3.43           | 57.95 ± 5.13           |
| Cellulose       | 32.15 ± 4.66           | 24.98 ± 2.66           |
| Lignin          | 32.67 ± 5.22           | 39.62 ± 2.11           |

Figure 1 shows the estimated water retention capacity (or rehydration process) of mulch fibers, measured as weight gain. This indirectly shows that rehydration rate decreased in time (rehydration rate could be thought of the first derivative concerning to time of the curve plotted here). Typically, the rehydration rate of dried fibers is higher during the initial period; then, it reaches a zero value. It finally tends to remain the same as time passes, indicating the beginning of the saturation condition. The rate of water uptake is high in the initial period because of the high-water activity gradient between the sample and surrounding media (here water). Over time, this difference is reduced, with consequent lower rate of rehydration. This behavior is typical of rehydration processes of vegetable fibers, fruits, grains, etc. [47,48].

**Figure 1.** Mulch moisture retention vs. time curve (points represent the average of three replicates and the bars the standard deviation).

The maximum time of the mulch capacity to retain moisture between its fibers was at eight hours, and its maximum retention capacity was almost 2.84 times its weight from 200 to 767 g (Figure 1). At subsequent time intervals, a gradual reduction in water retention was observed until it was rebalanced between 30 and 48 h.
After 24 h of being submerged for the swelling test, it was determined that the mulch absorbs water and swells 5.64 ± 0.72 times its initial mass 64.88 ± 13.83 g. Like in tensile tests, the standard deviation is high, which is justified considering the variability of the fibers with which the mulch was made.

### 3.3. Edaphic and Agricultural Variables

In the initial soil analysis, it was observed that the organic matter (OM) concentration was 1.81 ± 0.13%, and its main elements were Ca and Mg (Table 3). The use of mulch generated a significant increase in the OM and K concentration at values of 2.33 ± 0.25% and 0.91 ± 0.28 meq/100 gr, respectively, in T4 (with mulch + 129 mm of water) compared to the bare soil at the beginning of the experiment. Similar results were reported by [49], working with different mulches; they found that mulching did not affect soil bulk density, pH, or total nitrogen content, but consistently improved soil organic matter.

**Table 3.** Soil concentration of macro- and micronutrients, determined in T1: no mulch + 251 mm of water; T2: with mulch + 251 mm of water; T3 no mulch + 129 mm of water; T4: with mulch + 129 mm of water.

| Elements | Initial Sample | T1 | T2 | T3 | T4 |
|----------|----------------|----|----|----|----|
| %        |                |    |    |    |    |
| N        | 0.12 ± 0.01    | 0.16 ± 0.02 | 0.17 ± 0.02 | 0.14 ± 0.03 | 0.16 ± 0.00 |
| C        | 1.05 ± 0.07    | 1.11 ± 0.04 | 1.28 ± 0.15 | 1.17 ± 0.05 | 1.36 ± 0.14 |
| ppm      | 4.77 ± 0.45    | 4.84 ± 0.58 | 7.80 ± 2.88 | 5.71 ± 1.30 | 9.27 ± 3.71 |
| meq/100 gr | 0.35 ± 0.02   | 0.4 ± 0.08  | 0.91 ± 0.28 | 0.41 ± 0.08 | 1.14 ± 0.60 ** |
| Ca       | 18.78 ± 0.48   | 18.78 ± 0.48 | 16.68 ± 0.34 | 18.39 ± 0.27 | 18.51 ± 0.62 |
| Mg       | 12.5 ± 1.05 *  | 10.7 ± 0.35 | 10.54 ± 0.33 | 10.77 ± 0.14 | 10.46 ± 0.52 |
| %        |                |    |    |    |    |
| Zn       | 1.14 ± 0.22    | 9.65 ± 0.07 | 10.02 ± 0.09 | 9.71 ± 0.08 | 9.76 ± 0.22 |
| Cu       | 12.05 ± 0.29   | 1.16 ± 0.53 | 1.15 ± 0.79 | 1.06 ± 0.50 | 1.41 ± 1.49 |
| Fe       | 17.9 ± 2.11    | 20.26 ± 2.86 | 22.66 ± 3.06 | 20.8 ± 2.36 | 22.29 ± 3.82 |
| Mn       | 15.89 ± 7.15   | 19.27 ± 1.80 | 26.05 ± 5.14 | 21.11 ± 4.33 | 25.51 ± 7.15 |

* Concentration of primary elements in the soil at initial analysis. ** Significant increase comparison (Dunnett, α = 0.05) of the concentration of potassium (K) and organic matter (OM) in soils with and without mulch concerning the initial soil. PCP¹: Physical-chemical parameter.

There were no significant differences in the macro and micronutrient content between treatments. However, the tendency of average P and Mn concentrations in beds with mulch was higher; the continuous use of the mulch would gradually increase the concentration of these nutrients.

On the other hand, the differences in agronomic parameters between treatments with and without mulch were significant. For example, in Figure 2, it can be observed that plants sown in T2 and T4 showed a similar height at 56 d after transplant, 38.22 ± 9.93 and 37.6 ± 11.05 cm, respectively; whereas T1 and T3 had an average height of 30.60 ± 6.85 cm. Plants that grew in mulched beds registered an average height of 43.3 ± 9.25 cm at the beginning of the harvest cycle (at 63 d). It could be said that plants in mulched beds were, on average, 13 cm taller than the ones in bare soils.

More details are revealed through ANOVA about the effects produced by mulch and irrigation regime, as well as the interaction between these two variables (see Table 4). The first inspection of Table 4 shows that mulch has a significant effect (p < 0.05), while the irrigation regime does not. Graph visualization of this fact could be verified in Figure 3A. The figure’s right panel shows a strong mulch effect, represented by a high slope line. In contrast, the left panel, corresponding to irrigation, shows only a slight increase in the plants’ mean height when the irrigation regime changes.
Figure 2. Height of pepper plants under different treatments at different 63 days. T1: no mulch + 251 mm of water; T2: with mulch + 251 mm of water; T3 no mulch + 129 mm of water; T4: with mulch + 129 mm of water.

Table 4. Analysis of variance for factor and regression interactions of height, flowers/plant and harvest/plant.

| Source            | DF | Adj SS  | Adj MS  | F-Value | p-Value |
|-------------------|----|---------|---------|---------|---------|
| Height            |    |         |         |         |         |
| Model             | 3  | 479,173 | 159,724 | 17.77   | 0.001   |
| Linear            | 2  | 477,560 | 238,780 | 26.56   | 0.000   |
| IRRIGATION        | 1  | 8575    | 8575    | 0.95    | 0.357   |
| MULCH             | 1  | 468,985 | 468,985 | 52.17   | 0.000   |
| 2-Way Interactions| 1  | 1613    | 1613    | 0.18    | 0.683   |
| IRRIGATION*MULCH  | 1  | 1613    | 1613    | 0.18    | 0.683   |
| Error             | 8  | 71,921  | 8990    |         |         |
| Total             | 11 | 551,094 |         |         |         |
| Flowers/plant     |    |         |         |         |         |
| Model             | 3  | 66,721  | 222,402 | 3.66    | 0.063   |
| Linear            | 2  | 59,098  | 295,489 | 4.86    | 0.041   |
| IRRIGATION        | 1  | 0.163   | 0.1627  | 0.03    | 0.874   |
| MULCH             | 1  | 58,935  | 589,350 | 9.70    | 0.014   |
| 2-Way Interactions| 1  | 7,623   | 76,230  | 1.25    | 0.295   |
| IRRIGATION*MULCH  | 1  | 7,623   | 76,230  | 1.25    | 0.295   |
| Error             | 8  | 48,597  | 60,746  |         |         |
| Total             | 11 | 115,318 |         |         |         |
| Harvest/plant     |    |         |         |         |         |
| Model             | 3  | 398,402 | 132,801 | 19.01   | 0.001   |
| Linear            | 2  | 395,475 | 197,737 | 28.30   | 0.000   |
| IRRIGATION        | 1  | 950     | 950     | 0.14    | 0.722   |
| MULCH             | 1  | 394,525 | 394,525 | 56.47   | 0.000   |
| 2-Way Interactions| 1  | 2928    | 2928    | 0.42    | 0.536   |
| IRRIGATION*MULCH  | 1  | 2928    | 2928    | 0.42    | 0.536   |
| Error             | 8  | 55,888  | 6986    |         |         |
| Total             | 11 | 454,290 |         |         |         |

DF: Degree of freedom, Adj SS: Adjusted sums of squares, Adj MS: Adjusted mean squares.
The interaction between both variables is not significant either ($p = 0.683$). This result suggests that the irrigation dose considered as “low” when the experimental design was conceived did not produce enough stress on the pepper plants. An important region to be explored (and that was part of our initial goals) is one in which the crop is affected by water stress, but the mulch’s beneficial effects compensate such stress. This “compensatory effect” exerted by the mulch would be used to reduce irrigation to a minimum level without harvest appreciable loss.

This result also suggests that the mulch could have beneficial effects on a wide range of possible irrigation regimes without visible “twist or curvature” effects. It may represent an advantage in systems where irrigation cannot be calculated accurately or the rainfall changes abruptly, affecting the initially estimated calculations. Those results are evidenced in Figure 3D since the lines do not intercept, and a water supply increase leads to a

Figure 3. Effects of irrigation regime and mulch application on (A) height of pepper plants, (B) harvest/plant, and (C) basal diameter. Effect plot interaction between irrigation regime and mulch application measured on (D) height of peppers plants, (E) harvest/plant, and (F) basal diameter.
concomitant increase in the response variable.

Moreover, significant differences were found between treatments concerning the average flower number and fruits per plant. Once again, these differences’ main tendency was due to mulch use, regardless of the amount of water supplied (see Table 4). Similarly, as reported by [50], a drip irrigation system using straw mulch recorded the highest growth in plants and early flowering in tomato crops.

Some replicates of our experiment, flowers, and fruits produced in mulched beds almost doubled the number provided by treatments without coverage. Even though this seems to be the main trend, Table 4 shows that the model’s adjustment is weak, so these results should be handled with care (Model p-Value = 0.063). It must not be forgotten that these results correspond to the period from sowing until the beginning of the harvest cycle. It is prudent to review the rest of the harvest cycle to verify this trend.

When focusing on the entire harvest cycle (remember that it was harvested on days 64, 74, 99, 106, 119 post-transplant), the average of the variable “harvest/plant” in each of the treatments must be highlighted. It is perhaps an essential variable from an agronomic point of view, since it brings together the whole cycle, giving a clear idea of the global performance in each treatment. This response variable’s behavior is observed in Table 4, showing a significant effect ($p < 0.05$), while the irrigation regime does not. In general, it can be stated that mulched treatments doubled the harvest, compared with treatments without mulch (see Figure 4). Besides, it should be emphasized that the amount of water applied (129 mm or 251 mm) did not significantly affect the production of peppers in mulched beds, and the main effect was produced mostly by the mulch (Figure 3B,E). It shows that mulching fulfills its function of saving water, which would significantly reduce production costs by using a fraction of the water initially required by the crop.

![Interval Plot of HARVEST/PLANT vs Treatment](image)

**Figure 4.** Interval plot of “harvest/plant” between different treatments. Bars express a 95% confidence interval. T1: without mulch + 251 mm of water; T2: with mulch + 251 mm of water; T3 without mulch + 129 mm of water; T4: with mulch + 129 mm of water.

All these results are in line with those observed in the previously described variables; plants in mulched beds have much better growth parameters than those in bare soil, and there was no effect on the water applied as described by [51].

Concerning the analysis of the basal diameter, it showed similar but not strictly identical behavior than previously described variables (see Figure 3C,F). It was observed that plant diameter in T4 (mulch + 129 mm of water) was 29 and 38% higher than that of T1 and T3, respectively. Nonetheless, when T2 (mulch + 251 mm of water) response is observed, a lightly detrimental effect is present (but not statistically significant). In
conditions without mulch, the average basal diameter was \(11.50 \pm 0.90\) mm, while in mulched treatments, it was \(14.91 \pm 1.28\) mm.

Biomass production, both fresh and dry, was more abundant with mulched treatments. Like in all previously studied variables, the most significant effects were associated with mulch treatments, while irrigation regimes did not show significant differences. On average, the production of fresh biomass (total) in T2 and T4 (with mulch) was 84\% higher than in T1 and T3 (no mulch).

The dry weight of mulched treatments was 99\% greater than that of the treatments without coverage (see Table 5). These results coincide with those reported in tomato by [52]. They showed that plant height, fresh and dry vegetative biomass, number and weight of fruit/plant, and fruits circumference showed comparatively higher growth in mulched treatments. In the same line, [53] reported that mulching provides a healthier environment, allowing plants to become vigorous and resistant to pests, which could allow a yield increase and low use of insecticides.

Table 5. Fresh and dry weight of pepper plants. Different letters in the column indicate significant differences between treatments (Tukey-HSD, \(\alpha = 0.05\)). T1: no mulch + 251 mm of water; T2: with mulch + 251 mm of water; T3 no mulch + 129 mm of water; T4: with mulch + 129 mm of water.

| Treatment | Fresh Weight | Dry Weight |
|-----------|--------------|------------|
|           | Stems (g)    | Leaves (g) | Total (g) |
| T1        | 906.47 ± 207.14 B | 978.64 ± 160.79 AB | 1885.11 ± 367.80 BC |
| T2        | 1499.82 ± 90.90 A | 1419.16 ± 146.91 AB | 2919.97 ± 235.79 AB |
| T3        | 698.09 ± 235.82 B | 741.06 ± 275.23 B  | 1439.14 ± 510.45 C |
| T4        | 1641.84 ± 181.17 A | 1572.96 ± 406.32 A | 3214.79 ± 585.54 A |

Regarding the concentration of macro- and micronutrients in pepper leaves, it was observed that the concentrations of P, Zn, and Cu were higher in T2 (with mulch + 251 mm of water) in Table 6. Additionally, the concentration of N was higher in T3 (no mulch + 129 mm of water). No statistical differences between the treatments were observed in the concentration of K, Ca, Mg, Fe, and Mn. This analysis revealed that the content (concentration multiplied by the biomass) of some macro- and microelements was higher in the mulching treatments. The content of N was higher in T4 (with mulch + 129 mm of water). It can be concluded that the mulch improved the absorption of some nutrients in pepper plants, similar to what was reported by [54] on the effect of paddy straw mulch on N-use efficiency and essential oil yield in a multiharvested geranium crop (Pelargonium graveolens). The authors found that, by using paddy straw mulch, plant nitrogen uptake of planted and regenerated crops was increased by 33\% and 28.4\%, respectively, over the nonmulched control.
Table 6. Concentration and content of macro and micronutrients in pepper plants. Different letters indicate statistical differences between treatments (Tukey-HSD, α = 0.05) T1: without mulch + 251 mm of water; T2: with mulch + 251 mm of water; T3 without mulch + 129 mm of water; T4: with mulch + 129 mm of water.

| Elements | Unit    | Treatments | Concentration | Total Biomass | Content |
|----------|---------|------------|---------------|--------------|---------|
| N        | g/100 g | T1         | 3.87 ± 0.27   | AB           | 529.75 ± 114.7 | 20.5 ± 1.41 | C       |
|          |         | T2         | 2.53 ± 0.08   | C            | 894.77 ± 60.97 | 22.7 ± 0.74 | B       |
|          |         | T3         | 3.98 ± 0.64   | A            | 410.04 ± 164.35 | 16.3 ± 2.63 | C       |
|          |         | T4         | 2.99 ± 0.14   | BC           | 976.41 ± 179.85 | 29.2 ± 1.38 | A       |

| P        | g/100 g | T1         | 0.22 ± 0.04   | BC           | 529.75 ± 114.7 | 1.14 ± 0.19 | B       |
|          |         | T2         | 0.29 ± 0.01   | A            | 894.77 ± 60.97 | 2.60 ± 0.05 | A       |
|          |         | T3         | 0.18 ± 0.004  | C            | 410.04 ± 164.35 | 0.72 ± 0.02 | B       |
|          |         | T4         | 0.25 ± 0.04   | AB           | 976.41 ± 179.85 | 2.46 ± 0.37 | A       |

| K *      | g/100 g | T1         | 3.85 ± 0.21   | 529.75 ± 114.7 | 20.4 ± 1.10 | B       |
|          |         | T2         | 3.67 ± 0.01   | 894.77 ± 60.97 | 34.6 ± 0.13 | A       |
|          |         | T3         | 3.63 ± 0.09   | 410.04 ± 164.35 | 14.9 ± 0.37 | C       |
|          |         | T4         | 3.78 ± 0.33   | 976.41 ± 179.85 | 36.9 ± 3.19 | A       |

| Ca *     | g/100 g | T1         | 1.84 ± 0.16   | 529.75 ± 114.7 | 9.73 ± 0.84 | B       |
|          |         | T2         | 2.42 ± 0.43   | 894.77 ± 60.97 | 21.6 ± 3.82 | A       |
|          |         | T3         | 2.14 ± 0.08   | 410.04 ± 164.35 | 8.79 ± 0.32 | B       |
|          |         | T4         | 2.14 ± 0.22   | 976.41 ± 179.85 | 20.9 ± 2.11 | A       |

| Mg *     | g/100 g | T1         | 0.55 ± 0.07   | 529.75 ± 114.7 | 2.92 ± 0.38 | B       |
|          |         | T2         | 0.51 ± 0.07   | 894.77 ± 60.97 | 4.57 ± 0.62 | A       |
|          |         | T3         | 0.63 ± 0.07   | 410.04 ± 164.35 | 2.60 ± 0.29 | B       |
|          |         | T4         | 0.52 ± 0.06   | 976.41 ± 179.85 | 5.05 ± 0.63 | A       |

| Zn       | ppm     | T1         | 78.7 ± 7.87   | 529.75 ± 114.7 | 0.04 ± 0.004 | B       |
|          |         | T2         | 118 ± 6.59    | 894.77 ± 60.97 | 0.11 ± 0.01 | A       |
|          |         | T3         | 74.5 ± 12.26  | 410.04 ± 164.35 | 0.03 ± 0.01 | B       |
|          |         | T4         | 96.0 ± 14.55  | 976.41 ± 179.85 | 0.09 ± 0.01 | A       |

| Cu       | ppm     | T1         | 25.35 ± 1.12  | 529.75 ± 114.7 | 0.01 ± 0.001 | B       |
|          |         | T2         | 37.23 ± 1.90  | 894.77 ± 60.97 | 0.03 ± 0.002 | A       |
|          |         | T3         | 22.07 ± 1.05  | 410.04 ± 164.35 | 0.01 ± 0.0004 | B       |
|          |         | T4         | 31.30 ± 5.50  | 976.41 ± 179.85 | 0.03 ± 0.01 | A       |

| Fe *     | ppm     | T1         | 276 ± 64.98   | 529.75 ± 114.7 | 0.15 ± 0.03 | B       |
|          |         | T2         | 348 ± 76.79   | 894.77 ± 60.97 | 0.31 ± 0.07 | A       |
|          |         | T3         | 331 ± 74.06   | 410.04 ± 164.35 | 0.14 ± 0.03 | B       |
|          |         | T4         | 274 ± 37.30   | 976.41 ± 179.85 | 0.27 ± 0.04 | A       |

| Mn *     | ppm     | T1         | 88.1 ± 7.01   | 529.75 ± 114.7 | 0.05 ± 0.004 | B       |
|          |         | T2         | 91.7 ± 12.19  | 894.77 ± 60.97 | 0.08 ± 0.011 | A       |
|          |         | T3         | 92.9 ± 9.57   | 410.04 ± 164.35 | 0.04 ± 0.004 | B       |
|          |         | T4         | 95.7 ± 4.10   | 976.41 ± 179.85 | 0.09 ± 0.004 | A       |

* No statistical differences between treatments were observed in K, Ca, Mg, Fe, and Mn concentration.

In the present work, two results are worth noting: weed and temperature reduction in mulched treatments. In beds with coverage, a significant reduction of weeds, by 95%, could be observed, compared to uncovered beds (Figure 5A). Previous studies also show that the use of mulches reduces the number of weeds [55–57]. The considerable reduction of weeds allows the plants a higher growth and production since competition for light and nutrients decreases. On the other hand, average temperature in mulched beds was 18.6 °C, while the soils without coverage reached 21.2 °C (Figure 5B). It is well known that temperature plays a pivotal role in plant growth. In addition to the reduction of weeds, one of the benefits of mulch is the maintenance of soil temperature, which would have positive repercussions on the development of roots and beneficial microbial populations. Agiero et al. [58], reported those influences in microflora behavior and stated that mulching increased soil microbial flora and helped maintain favorable soil temperature for microbial growth. Bhagat et al. [59], also indicated that mulches enhance soil environment, promote
microbial flora, and increase crop yield. In addition, the authors also concluded that mulch increased the minimum soil temperature by 2–3 °C and lower the maximum by 2–8 °C.

Figure 5. (A) Number of weeds per square meter (w/m²) in beds with and without mulching at 21, 35, and 56 days post-transplant of pepper; different letters in the column indicate significant differences between treatments (Tukey–HSD, α = 0.05). (B) Effect of the mulching on soil temperature at 28, 35, 42, 56, and 63 days; points express the average of three replicates and the bars the standard deviation.

Our findings were similar to the results obtained by [59], but no minimum and maximum temperatures were recorded. Instead, the temperature measurements are punctual; however, when the coefficients of variation (CoefVar) are assessed, a similar pattern emerges (see Table 7). The CoefVar is a measure of spread that describes the difference in the data, relative to the mean; it is adjusted in a dimensionless scale. Because of this, it is frequently used to compare the variation in data that have different means (or units). Table 7 shows that the soil temperature measurements associated with nonmulched treatments (T1 and T3) have greater dispersion than those associated with mulched ones (T2 and T4). It could suggest that mulching contributes to the stability of the microbiome by maintaining the soil temperature, varying within a narrow range, and, in this way, providing a more stable habitat compared to bare soil. The temperature stability, in turn, conditions other physical-chemical variables that have a decisive influence on all agronomic response variables measured throughout this work. Instead of an increase in the minimum soil temperature and a decrease of maximum, like in [59] a complete displacement of the temperature interval was found. It should be considered that the climatic conditions of both experiments are very different. While [59] faced low temperatures during their research, ours was developed during the dry season and latitude 0° at the equator.

Table 7. Basic statistics for the variable “soil temperature.” T1: without mulch + 251 mm of water; T2: with mulch + 251 mm of water; T3 without mulch + 129 mm of water; T4: with mulch + 129 mm of water.

| Variable | Treatment | N  | Mean   | SE Mean | StDev  | CoefVar |
|----------|-----------|----|--------|---------|--------|---------|
| Temperature | T1 | 3 | 20.917 | 0.560 | 0.969 | 4.63 |
|          | T2 | 3 | 18.506 | 0.150 | 0.259 | 1.40 |
|          | T3 | 3 | 21.436 | 0.385 | 0.667 | 3.11 |
|          | T4 | 3 | 18.700 | 0.150 | 0.260 | 1.39 |

3.4. Water Use Efficiency (WUE)

The first result that attracts attention when focusing on WUE is visualized from the comparison of treatments T1 and T3 (see Table 8). In these, it can be observed that the same
amount of harvest is obtained after doubling water supply, or equally that the amount of irrigation can be reduced by half, without appreciable loss in the yield. Results such as these have been reported (among other researchers) by [60] working with lettuce in Mallorca. The logical question that arises is: Why do farmers not reduce irrigation? Medrano et al. [60], provides a possible answer: Farmers, to obtain uniform harvests, in plots that are not usually uniform, exaggerate irrigation. This fact, coupled with the impossibility in most cases of efficiently controlling the quantities of water supplied, ultimately results in excess irrigation. These types of practices are estimated to be disappearing as improvements to irrigation systems, such as sectorization and automation, are implemented. That is, as precision agriculture is adopted, the WUE of crops will be strongly increased.

Table 8. Water use efficiency in different treatments based on pepper crop yield.

| Treatment | Application of Water per Plant | Harvest per Plant | WUE  |
|-----------|--------------------------------|------------------|------|
|           | m³                             | kg               | kg/m³|
| T1: No mulch + 251 mm of water | 0.098                      | 0.45 ± 0.11      | 4.59 ± 1.13 |
| T2: With mulch + 251 mm of water | 0.098                      | 0.78 ± 0.11      | 7.96 ± 1.13 |
| T3: No mulch + 129 mm of water | 0.049                      | 0.40 ± 0.11      | 8.16 ± 2.26 |
| T4: With mulch + 129 mm of water | 0.049                      | 0.79 ± 0.11      | 16.12 ± 2.26 |

Another interesting fact associated with WUE and mulch use can be seen when comparing treatments T1 and T2. It demonstrates mulching produces an effect of almost doubling the harvest per plant, with a concomitant increase in WUE, regardless of the irrigation regime (see Table 8). Finally, when comparing the mulched treatments (T2 and T4), T4 doubles the WUE of T2 since it produces the same crop using half of the irrigation water. It is shown that the use of mulch plays a decisive role in the increase in WUE.

4. Conclusions

Characterization results of the mat mulch indicate it has enough strength to be applied and manipulated in the field. When degrading it will incorporate nutrients such as P, K, and Ca into the ground; as the process continues, it incorporates other nutrients stored in its structure (such as Cu, Mn, Zn). The mulch has shown a significant influence on agronomic variables such as the plant's height and diameter, the number of their flowers and fruits, as well as the harvest per plant and plant biomass, particularly with the application of the 129 mm water irrigation regime. Furthermore, it improves the absorption of some nutrients, as evidenced of some important minerals in the biomass (e.g., K).

In parallel, the use of the mat mulch contributed to two other fundamental issues, the soil’s thermal regulation and the reduction of weeds. Soil temperature was lower than the air temperature, contributing to water retention on the ground. Beds with coverage reached up to 95% weeds reduction. In terms of the water use efficiency, the mat mulch reduced the soil water loss through evaporation, allowing an adequate water supply to the crop; this is clearly visible when comparing the results between T1 (no mulch + 251 mm) and T4 (with mulch + 129 mm). Finally, to achieve total biodegradability of mulch, we would consider replacing the synthetic yarn with a biodegradable one, which allows the same initial field manipulation. For future research, we suggest studying the nutrient’s use efficiency, its influence over soil microflora, and its use in crops with high water requirement.

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