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Testing the suitability of a terrestrial 2D LiDAR scanner for canopy characterization in greenhouse tomato crop

Jordi Llop [1], Emilio Gil [1,*], Jordi Llorens [2], Antonio Miranda-Fuentes [2] and Montserrat Gallart [1]

[1] Universitat Politècnica de Catalunya - Department of Agrifood Engineering and Biotechnology, Esteve Terradas, 8, 08860 Castelldefels (Barcelona), Spain; E-Mail: jordi.llop-casamada@upc.edu (JL); Emilio.gil@upc.edu (EG); Montserrat.gallart@upc.edu (MG)
[2] Universidad de Córdoba, Área de Mecanización y Tecnología Rural, Dpto. de Ingeniería Rural. Córdoba 14005; E-Mail: ir2llcaj@uco.es (JL) ; antonio.miranda@uco.es (AM-F).

* Correspondence: Emilio.gil@upc.edu; Tel.: +34-935-521- 099

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Abstract:

Canopy characterization is a key factor to adjust pesticide dosage to the amount of vegetation. This fact becomes especially important when the target is a fresh exportable vegetable like tomato produced in greenhouse. The particularities of this crop, whose plants are thin, tall and planted in pairs, make difficult their characterization with electronic methods. The present study attempts to assess the accuracy of the terrestrial 2D LiDAR sensor for determining major canopy parameters related to its volume and density and it establishes useful correlations between manual and electronic parameters for leaf area estimation. The experiments were carried out at three different commercial tomato greenhouses planted in a twin row system. The electronic characterization was done with a LiDAR sensor (LMS-200, SICK) of 180º angle measurement by scanning the pair of plants by both sides. The main parameters obtained were: canopy height, canopy width, canopy volume and leaf area. From these, other important parameters were calculated, like the tree row volume (TRV), the leaf wall area (LWA), the leaf area index (LAI) and leaf area density (LAD). A general overview of the results show an overestimation of the parameters with manual measurements due to the high definition of the profile obtained with this sensor. The estimation of the canopy volume with the electronic device showed to be a reliable parameter to estimate the canopy height, volume and density. Also, the LiDAR scanner demonstrated to be able to assess the high variability of the canopy density along the row, resulting to be an important tool for canopy maps generation.

Keywords: greenhouse; tomato crop; LiDAR sensor; canopy characterization; LAI

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1. Introduction

The public concern due to the environmental problems associated with the inaccurate pesticide application process led the European Administration to develop a regulatory framework that was established with the European Directive 2009/128/EC [1]. In this document, the need to improve the efficiency in the use of Plant Protection Products (PPPs) is remarked, and one of the guidelines to achieve this goal is the dose adjustment to the real needs, avoiding overdosing and, therefore, unnecessary PPP losses to the environment.

The greenhouse tomato crop, grown to be consumed as a fresh product, is very important in Spain, with a cultivated area of 6189 ha [2]. Being important an accurate application of pesticides in all kind of crops or circumstances, those related to fresh products to be directly commercialized in the market, need a very accurate and safe use of pesticides in order to prevent health risks. Pesticide residues on vegetables constitute a possible risk to consumers and have been a human health concern [3]. In contrast, even though some works have been done at evaluating the optimal volumes to be applied [4–5], not enough research has been done to relate all the parameters affecting the relationship between the canopy characteristics and the amount of PPP according to the real needs.

Greenhouse tomato rises from the ground and develops a long stem, which is fixed by the farmer to a fixed structure to make it stay in a vertical disposition. Therefore, this crop belongs to the group of those called 3D crops, i.e., crops that present a complex geometry for the sprayer, in opposition to the arable crops, that are treated as if they were a flat, 2D target. The constant pressure that generates a constant liquid flow rate has shown to not to be valid for 3D crops [6], as the varying geometry of the different individuals make very difficult to set a general application volume that results in a satisfactory application quality. This fact led the researchers to set other systems that focus on different parameters relative to the canopy structure. Thus, the first two methodologies to appear were the Tree Row Volume (TRV) and the Leaf Wall Area (LWA). The TRV method consists of calculating the canopy volume by assuming its prismatic shape, so the canopy height and width, along with the row spacing, are the base parameters to determine the TRV, expressed in m^3 canopy per ha ground [7–8]. The application volume will be proportional to this TRV parameter according to a specific coefficient that will have different values according to the crop [9–11]. The Leaf Wall Area, on the other hand, is based on the assumption that the canopy sides are completely flat, so they form a "wall". The main parameter to calculate LWA is the canopy height [12], so this method ignores the canopy width. The LWA is expressed in m^2 leaf wall area per ground ha. The sprayed dose is calculated for every 10.000 m^2 LWA. These two systems are well implanted and nowadays there is a general discussion between the countries of the European Union in which of these systems should be used as the standard label dosing system for all the crops [13–14]. Nevertheless, in the last years, different authors proposed alternative systems as the TRV and LWA do not take into account a canopy parameter of major importance, the leaf density [14], so this method needs to be completed with further information. Therefore, different dosing systems appeared for different crops, as vineyards, citrus or fruit trees, like apple [6, 15–18]. Even though they differ in their basis, assumptions and calculations, they all have something in common: they have to rely on an accurate canopy characterization system.

Canopy characterization is a complex task that has been solved in the last years in very different ways. The canopy characterization methods can be classified in two general categories: manual and electronic methods. The manual methods are those that are based on manual measurements performed with measuring tape, topographic milestone, etc. These methods vary according to the canopy structure, and are much simpler in hedgerow orchards than in isolated trees or plants. Even though they are reliable, fast and simple to use for the farmer, they become less useful for more advanced task such as generating prescription maps for proportional spray application, like the one proposed by the aforementioned dosing systems. In addition, the canopy density results extremely difficult to evaluate with those methods, being necessary the complete defoliation of a representative sample of plants to obtain reliable values. Therefore, the electronic methods seem to be a very appropriate option to accomplish the requirements of the dose adjustment. Among the electronic characterization methods, the more frequent are the ultrasonic sensors [18–20], the stereo vision [22], the light sensors [23] and the LiDAR scanners [24–29]. According to Rosell and Sanz [30], LiDAR is the most accurate technology to characterize the canopy, and in fact it showed to be very reliable at predicting canopy parameters in different studies [20, 24, 31]. The LiDAR scanner is based on the principle of Time-Of-Flight (TOF) to calculate distances, i.e., the sensor measures the elapsed time between a laser beam emission and reception and automatically calculates the distance to the target point [32]. This process is repeated along a plane in 2D scanners or in three dimensions, by rotating the scanning plane, in 3D LiDAR. The 2D sensor is cheaper and can have a third coordinate by moving it along the axis perpendicular to the scanning plane [24, 28], so it was more frequent for canopy characterization.

The particularities of the tomato plants, which are thin, tall and planted in pairs, make difficult their characterization with electronic methods, as it is difficult to identify the parameters related to each individual plant. Furthermore, the narrow row spacing limits the field of view of the sensors used. The aims of the present study are: 1) To assess the accuracy of the LiDAR sensor for determining major canopy parameters related to its volume and density, 2) To establish useful correlations between manual and electronic parameters for the leaf area estimation, 3) To take advantage of the LiDAR technology to assess the variation of the canopy density throughout the row, for being the basis to generate canopy density maps for pesticide dose adjustment.

2. Materials and Methods

2.1. Experimental fields.

The experiments were carried out in three different tomato cultivar greenhouses (GH) located in El Ejido (Almería, Spain) (36° 45′ 22.90″ N; 2° 48′ 34.89″ W) and in Viladecans (Barcelona, Spain) (14° 18′ 46.46″ N; 2° 1′ 48.44″ W), both important fresh productive areas in the Spanish Mediterranean coast. The greenhouses had tomato crops of the varieties *Velasco* and *Barbastro* that were disposed in similar plantation patterns (Table 1). The plants were planted in a twin row system (Figure 1a) where the crop was planted by pairs on the same row. The three greenhouses had a main corridor with adjacent and perpendicular rows (Figure 1b). The row spacing, *rs*, the plant spacing in the row, *ps*, and the twin plant spacing, *tps*, are specified in Table 1 and represented in Figure 1b.

Table 1. Main characteristics of the experimental fields.

Greenhouse ID	**Location**	**Plant layout** (row spacing x plant spacing) *(m x m)*	**Crop**
1	El Ejido (Almería)	2.5 x 0.4	*Solanum lycopersicum* L. cv. Velasco
2	El Ejido (Almería)	2.8 x 0.4	*Solanum lycopersicum* L. cv. Velasco
3	Viladecans (Barcelona)	2.0 x 0.4	*Solanum lycopersicum* L. cv. Barbastro

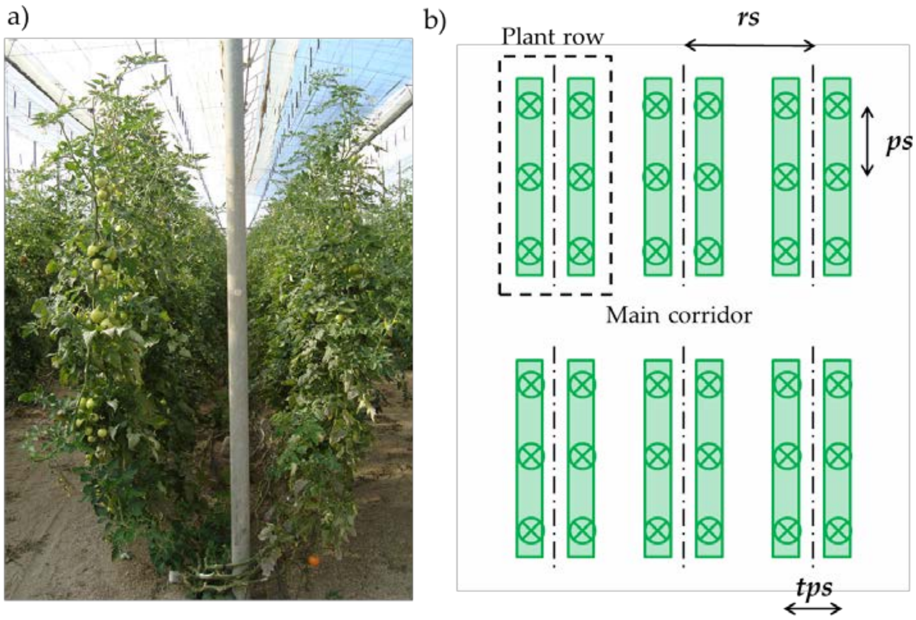

Figure 1. (**a**) Twin plantation system; (**b**) Plant disposition inside the greenhouse, with row spacing, *rs*, plant spacing in a row, *ps*, and twin plant spacing, *tps*.

2.2. Manual canopy characterization

For the manual canopy characterization, the total canopy height, H_M, and the canopy width, W_M, were measured along the row. The measurements were performed with a measuring tape by the same operators in the three fields of study, with 30 replications per field of study for each measurement. The H_M was measured from the lowest leaves in the plant stem to the top leaf of each plant (Fig. 2). In the case of the canopy width, measures were taken from the outer to the inner part of the canopy, measuring separately each plant of the twin plant system grow (Fig. 2).

The total leaf area per single plant was also determined. Thus, plants were collected by pairs, 2 pairs (4 plants) for greenhouses 1 and 2 and 3 pairs (6 plants) for greenhouse 3. They were appropriately stored in sealed plastic bags. Then, in laboratory conditions and before the leaves had dried, they were removed from the plants and subsamples of 80 g weight were planimetered with a leaf planimeter (LI-COR LI 3100C, Lincoln, NE), obtaining the total leaf area of the subsample (cm^2) and allowing the researchers to obtain the leaf area-weight ratio [4, 33, 34], which enables to obtain the leaf surface by only weighing the leaves, saving time.

From these measured parameters, it was possible to calculate others, as the Tree Row Volume, TRV [7, 33, 35], the Leaf Wall Area, LWA [36, 37], the Leaf Area Index, LAI, and the Leaf Area Density, LAD [38, 39].

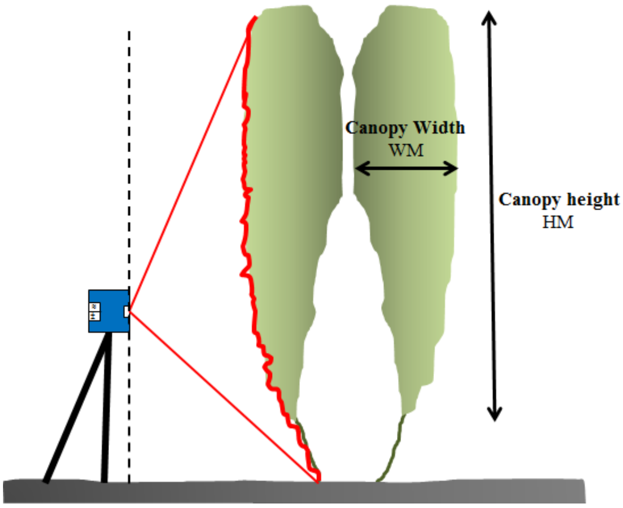

Figure 2. Measured parameters for the manual canopy characterization and LiDAR scanner disposition.

2.3. LiDAR canopy characterization.

2.3.1. Canopy scanning

The scanner used for the study was a terrestrial 2D low-cost general-purpose LiDAR (LMS-200, Sick, Düsseldorf, Germany). This is a fully-automatic divergent laser scanner based on the measurement of time-of-flight (TOF) with an accuracy of ±15 mm in a single shot measurement and 5 mm standard deviation in a range up to 8 m [20]. The sensor has a maximum scanning angle of 180 degrees and a selectable angular resolution of 1º, 0.5º or 0.25º, though the first one showed to be accurate enough for canopy characterization studies [40], so it was chosen for the present work. The device was fed at 24 V voltage by an autonomous battery and it was connected to a laptop via RS-232 Serial port for the data transmission.

The sensor was set in the center of the space between the crop rows and it was mounted opposed to the canopy in a way that it can properly scan the whole plants, from the base to the top (Fig. 2). The sensor was then moved along a constant track, scanning the pair of plants by both sides. Even though it was not possible to scan the same plant from both sides because of their paired disposition, the high resolution of the scanner made possible that a high percentage of the laser beams penetrate the first plant and scan the second. Furthermore, three replications per side and canopy section were undertaken.

During the scanning process, two types of structures were used: in greenhouses 1 (GH1) and 2 (GH2), the LiDAR sensor was mounted on a mobile platform that was manually pulled at a constant average speed (0.06 $m \cdot s^{-1}$±0.009) to make it slide along an aluminum rail of 2.4 m long mounted on trestles (Fig. 3b). At greenhouse 3 (GH3), the LiDAR sensor was mounted on an autonomous spraying platform described in Balsari *et al.* [41] (Fig. 3c). This platform was moved by an electric engine and commanded by remote radio control. In both cases data acquiring laptop was mounted on the platform to ease the wiring connections.

Due to mobility of the autonomous platform in the GH3, it was possible to scan the whole tomato row (23.4m long) by both sides of the canopy with 3 replications. These measurements enables to obtain information of the canopy variation in the row. .

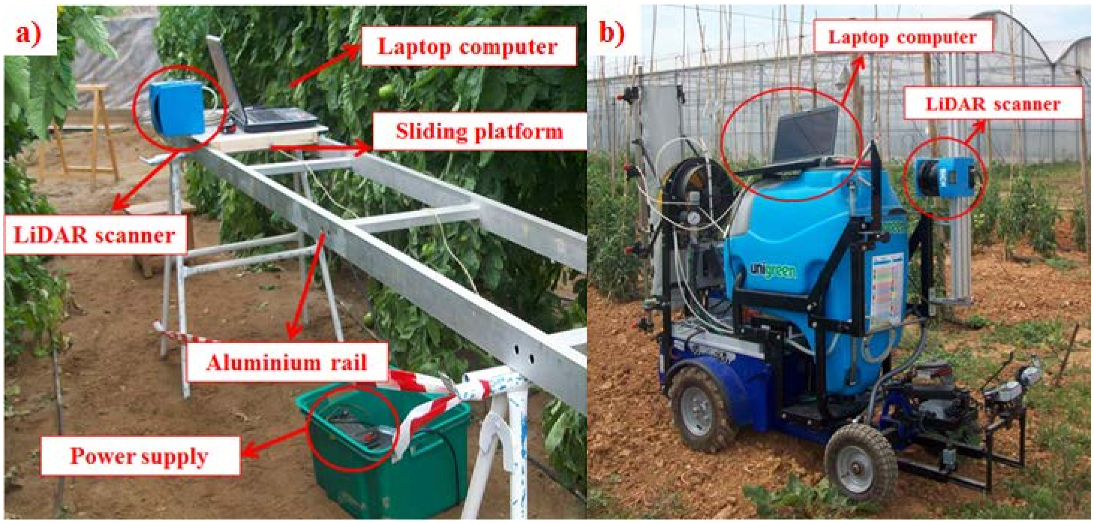

Figure 3. (**a**) Fixed structure of the LiDAR support system for measurements in greenhouses 1 and 2. (**b**) LiDAR scanner mounted on a radio control mobile platform for measurements in greenhouse 3.

2.3.1. Data processing

Data from LiDAR sensor was obtained in polar coordinates (each point has an angle direction and distance response). To manage the information, it was needed to convert raw data to XYZ coordinates with R-software® (3.0.2) (R Development Core Team, 2013) were X axis corresponds to the width of the plant, Y axis is the height of the plant and Z axis is the length of the row (Fig. 4a).

Due to the fact that two different structures were used to carry the LiDAR sensor to take the measurements there could be differences in the analyzed values. Furthermore, the forward speed of the sensor was irregular among different replications (coefficient of variation 16.8%) in the case of the fixed structure as it was manually driven. Therefore, all the data were normalized by taking into account the forward speed of the mobile sensor and the scanning frequency (Hz). This speed was calculated in the analysis process as the data acquisition system registers the time elapsed since the beginning of the data recording, and taking into account that the LiDAR track's length was known.

Once the data were appropriately normalized, results were imported in the CloudCompare ® software in order to see the LiDAR points cloud in 3D and to check that there were no problems or irregularities in the data acquisition process or in the data normalization. As the LiDAR sensor does not only scan the plants, but the greenhouse's top and ground and the sensor support system as well, it was necessary to define and select the points that belong to the canopy from the others. This process was arranged for each scanning file (by side) by observing the point cloud from a Z axis with orthographic projection and determining some border points by setting one of known coordinates and obtaining the rest from the first (Fig. 4a). After that process, both sides of scanned plants where manually aligned and positioned to define the whole canopy structure (Fig. 4b)

After this first approach, it was necessary to delimitate the points belong to each one of the two paired plants (Fig. 4b). This process was carried out manually by determining the center between them, which was assigned as (0,0) coordinate.

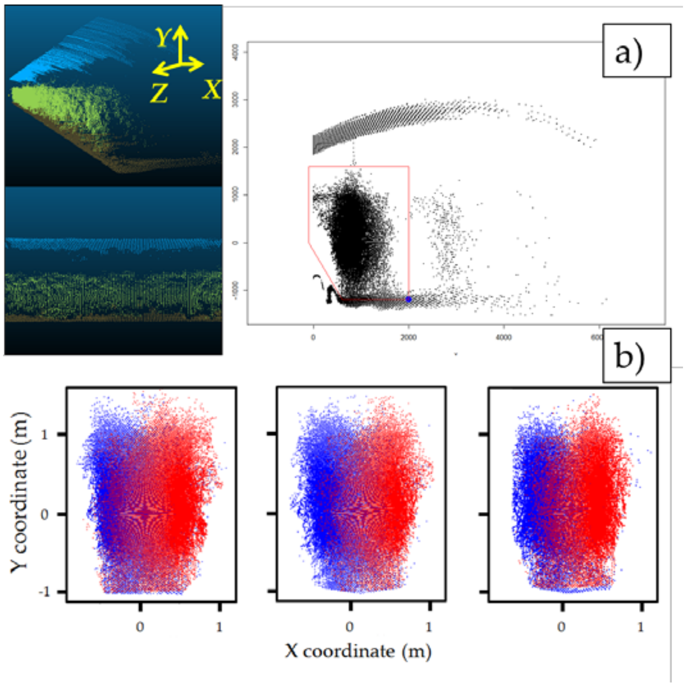

Figure 4. (**a**) LiDAR points cloud from one side in CloudCompare ® software with coordinate system and canopy delimitation procedure. (**b**) Plant delimitation process from twin plants (three replications).

At this stage, it was possible to obtain or calculate different parameters from the LiDAR points cloud, as the canopy height, H_L and width, W_L, the number of points on the target, IMP, and the canopy volume, V_L.

To calculate H_L, the difference between the highest and lowest points in each LiDAR slice (Fig. 4a), i.e., the maximum length in Y axis for each LiDAR profile, was determined. H_L was then calculated as the 95% of the maximum value among all that were determined previously. This 95% value was chosen to filter possible unusual profiles or data errors that could affect the reliability of the measurement. W_L is calculated by determining the half of the total width, measured on X axis, of each two paired plants. Once this distance was known, W_L was obtained as the 95% of the value, for the aforementioned reasons.

IMP parameter was determined as the number of LiDAR beams that impacted on the canopy per row length unit (impacts · m^{-1}). This parameter was included in the analysis process due to its significant correlation with manually measured LAI values in a previous research performed in vineyard [20]

In order to obtain the canopy volume per single plant, V_L, the methodology described in Xu *et al*. [41] and in Miranda-Fuentes *et al*. [40] was applied. This methodology is based on dividing the point cloud corresponding to the whole canopy in horizontal slices of a certain height, Δh. Next, all the points belonging to the same slice are projected on the same horizontal plane. Then, their external perimeter is delimited by using the Convex hull algorithm [43], and its inner area, A_i, determined. The volume of each slice, V_L, can be calculated as its internal area, A_i, by its height, Δh. The total volume of the plant is, therefore, calculated as expressed in Eq. 1.

$$V_L = \sum_{i=1}^{n} A_i \times \Delta h, \quad (1)$$

where n is the number of horizontal slices, V_L is expressed in m^3, Ai in m^2 and Δh in m.

As it is evident, the lower the Δh, the higher the vertical resolution of the method. In some works, Δh values of 0.001 m have been used [42]. Nevertheless, values of 1 cm showed to be accurate enough in previous studies [40] and accelerate the calculation process. Therefore, Δh value for the present study was 0.01 m.

2.3. Statistical analysis.

The statistical analysis adopted was a linear correlation between all measured and calculated parameters, using statistical R-Software ® (3.0.2) (R Development Core Team, 2013) with the *Agricolae* package. The data analysis related all the measured and calculated results to identify the most significant and interesting correlations between them, always considering the manually measured parameters as a reference.

A Shapiro-Wilk test ($p > 0.05$) [44, 45] and a visual inspection of the data histograms, normal Q-Q plots and box plots were performed to ensure that the data were normally distributed for all the cases. The interest of the linear correlations between the parameters obtained from the manual characterization, H_M, W_M, LAI, TRV, LAD and LWA, and those obtained from the LiDAR scanning of plants. H_L, W_L, V_L and IMP was evaluated with the correlation p-values and their determination coefficients (R^2).

3. Results

3.1. Parameters from the canopy characterization

A resume of those parameters obtained from the characterization can be found in Table 2.

Table 2. Geometrical and density values for all the measured and calculated parameters.

	Parameter		Greenhouse ID		
			1	2	3
Manual characterization	Manual height	H_M (m)	2.19 ± 0.02	2.50 ± 0.02	1.96 ± 0.04
	Manual width	W_M (m)	0.62 ± 0.02	0.43 ± 0.04	0.53 ± 0.01
	Tree Row Volume	TRV (m^3 ha^{-1})	10882 ± 397	7711 ± 212	10397 ± 252
	Leaf Wall Area	LWA (m^2 ha^{-1})	35111 ± 360	35683 ± 290	39170 ± 755
	Leaf Area Density	LAD (m^2 m^{-3})	5.81 ± 0.28	3.15 ± 0.15	5.30 ± 0.19
Electronic characterization	LiDAR Height	H_L (m)	1.90 ± 0.07	2.12 ± 0.01	1.93 ± 0.03
	LiDAR Width	W_L (m)	0.71 ± 0.02	0.64 ± 0.02	0.59 ± 0.03
	LiDAR volume	V_L (m^3)	1.13 ± 0.07	1.32 ± 0.03	2.42 ± 0.12

As it can be seen, the three fields of study had canopies of similar height characteristics. The maximum height of the plants grown is determined by the structure of the greenhouse instead of the growth of the plant, in which the stems are fixed to the greenhouse structure when they grow up to that level, continuing the growing process downwards, towards the ground. The canopy width is quite different overall in GH2, which presents also a low value of LAD. It is necessary to remember that width values were measured from the center between the two paired plants to the edge of each plant. These two parameters were very constant in all the studied fields, and specially the height.

The lowest value of TRV is found in GH2 (7771 $m^3 \cdot ha^{-1}$) that is strongly different from GH1 and GH3 (10882 and 10397 $m^3 \cdot ha^{-1}$ respectively). This differences can be explained by the difference in canopy width measured. Therefore the LWA did not follow the same trend that the TRV, having its maximum value in GH3, with 39170 m^2 LWA $ha^{-1}$and very similar values in GH1 and GH2.

The LAD was the lowest for GH2 (3.15 m^2 m^{-3}), and very similar for the other two fields (5.81 and 5.30 m^2 m^{-3} for GH1 and GH3, respectively).

As to the electronically measured parameters, the LiDAR height, H_L showed to be, in general, lower than the manually measured, H_M, with a mean value 12.12% lower. Nevertheless, the H_L parameter followed a similar trend than the H_M, with the maximum height being measured in GH2. The canopy width, on the other hand, was over-estimated by the scanner, but this occurred mainly in the case of GH2, in which the electronic method resulted in a 48% increment on the canopy width with respect to the manual measurements.

As to the Standard Errors (SE) in the measurements, they are in general low, being below 10% in all the cases and in most of them below 1%. By comparing the SE obtained for all the parameters in the three GHs, they result very similar in the geometrical measurements, and slightly higher for the case of the LAD parameter, what is normal if taking into account the variability of this parameter along the canopy.

3.2. Correlations among parameters obtained with manual and electronic methodologies.

Table 3 shows the determination coefficients (R^2) for all the paired linear correlations among all the parameters related to the canopy volume and density.

Table 3. All possible comparisons among all the measured and calculated parameters related to the canopy volume and density.

			Manual measurements						LiDAR measurements			
			H_M (m)	W_M (m)	LAI (m^2 m^{-2})	TRV (m^3 ha^{-1})	LWA (m^2 ha^{-1})	LAD (m^2 m^{-3})	IMP (m^{-1})	H_L (m)	W_L (m)	V_L (m^3)
Manual	H_M	(m)	1	0.29**	0.60**	0.50**	0.21*	0.53**	0.20*	0.59**	0.003	0.69**
	W_M	(m)		1	**0.70****	0.86**	0.01	0.65**	0.20*	0.52**	0.10	0.16
	LAI	(m^2 m^{-2})			1	**0.89****	0.02	0.97**	0.01	0.52**	0.01	**0.36****
	TRV	(m^3 ha^{-1})				1	0.08	0.79**	0.03	0.46**	0.01	**0.37****
	LWA	(m^2 ha^{-1})					1	0.01	0.51**	0.004	0.29**	0.33**
	LAD	(m^2 m^{-3})						1	0.01	0.47**	0.01	0.32**
LiDAR	IMP	(m^{-1})							1	0.0001	0.17	0.27*
	H_L	(m)								1	0.10	0.31**
	W_L	(m)									1	0.03
	V_L	(m^3)										1

Considering the height (H_L) parameter obtained with the LiDAR it has been significantly correlated with the manually measured height, H_M ($R^2 = 0.59$), with the manual width, W_M ($R^2 = 0.52$) and with TRV measured value ($R^2 = 0.46$). Nevertheless, there is no correlation between H_L and LWA ($R^2 = 0.004$). This could be due to the fact that this parameter was not proportional to the canopy height in the three GHs, being the maximum in GH3 even when the maximum height was found in GH2 (Table 2).

The LiDAR width, W_L, on the other hand, it was only significantly correlated with the LWA, even LWA calculation is not affected by the canopy width this correlation presented shows the importance of the width in this type of crops where the height is limited by the greenhouse structure.

The LiDAR volume, V_L, seems to be the most reliable parameter to estimate the canopy geometrical characteristics, as it is significantly correlated with H_M, TRV and LWA, with determination coefficients of 0.69, 0.37 and 0.33, respectively. As it can be seen, determination coefficients for TRV and LWA are very similar, and for being statistically reliable, this parameter could be the most complete for the estimation of those two parameters.

All the correlations between canopy density parameters, LAI and LAD, and the other parameters are included in Table 3. As it can be seen, there are interesting correlations among some manually measured geometrical parameters, like H_M and W_M, with the canopy density. In fact, both parameters are significantly related to the LAI ($R^2 = 0.60$ and $R^2 = 0.70$ for H_M and W_M, respectively), and to the LAD ($R^2 = 0.53$ and $R^2 = 0.65$ for H_M and W_M, respectively), what is not surprising as both density parameters are closely related. TRV values are highly correlated to LAI and LAD values, with determination coefficients of $R^2 = 0.89$ and $R^2 = 0.79$, respectively. LWA values, on the other hand, showed to not to be appropriate estimators of the leaf density, showing no significant correlations. The IMP parameter, expressed as the number of LiDAR impacts per length unit and that gave strong correlations with the leaf density parameter in previous works, showed to not to be accurate for predicting LAI or LAD values in tomato plants. More tests needs to be arranged in order to identify the reason of this difference.

Figure 5 shows the correlations between LAI and V_L (Fig. 5a) and between LAI and TRV (Fig. 5b). As it can be seen, the TRV values are well aligned with those of LAI. V_L, on the other hand, have a lower determination coefficient, $R^2 = 0.36$.

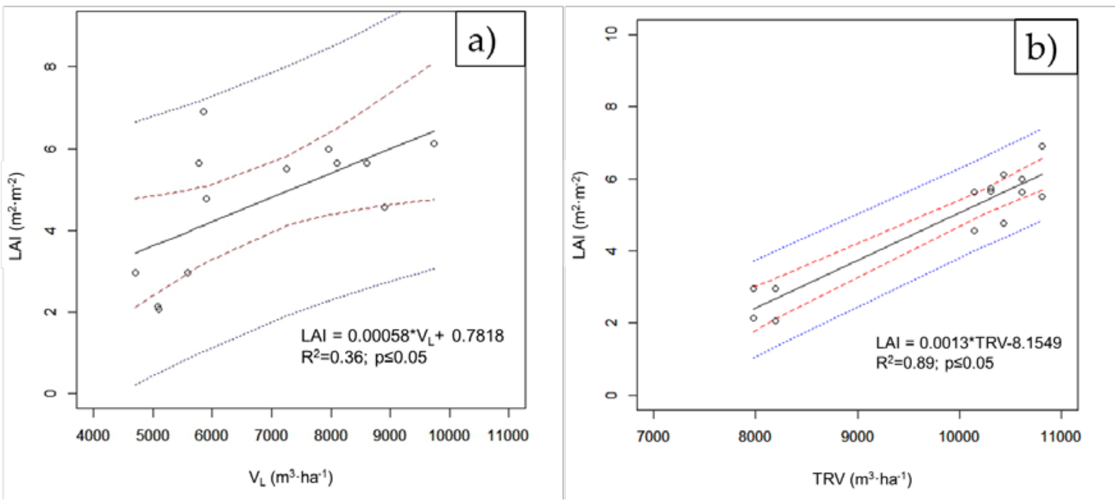

Figure 5. Linear correlations between (**a**) LAI and VL, and (**b**) LAI and TRV

3.3. Canopy characterization along a row from the LiDAR scanner measurements.

By means of the mobile platform it was possible to scan the whole row from the two sides. As an example of the variation of the vegetation along the row, LAI parameter was used. This estimation was based on the V_L, as it showed to be the most accurate for having the maximum determination coefficient among the studied parameters. The calculated variation of the LAI parameter in GH3 is represented in Figure 6. In this graphic the variation of the LAI value is calculated every 10 cm.

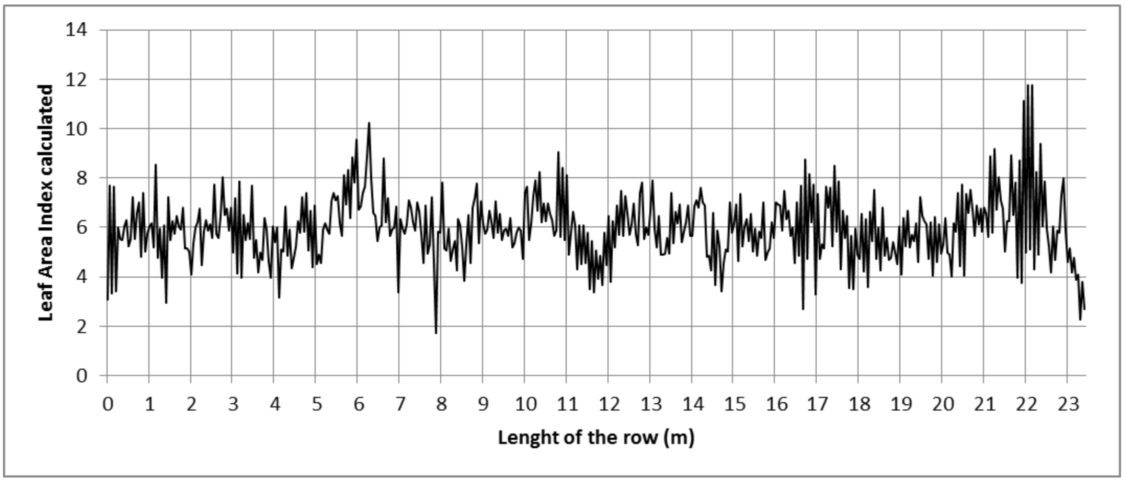

Figure 6. Calculated LAI variation along the scanned row in GH3.

Even though the variation range keeps relatively constant along the row, the continuous changes in the canopy reflect the important variation in LAI. Values usually range from 3 to 9, with exceptions like those found for the Z positions 6 m, 8 m and 22 m. The variation rate, calculated as the times that LAI varies in a value above 10% per linear meter, has a mean value of 10 m^{-1}. As it can be seen, values observed in the Figure 6 are in line with the LAI mean value shown in Table 2 (5.9). It is not the case of the Standard Error, which was found to be very small in the manual measurements (0.17).

4. Discussion

A 2D LiDAR scanner was used to electronically obtain canopy parameters related to the canopy volume and density in a very difficult crop because of its structure. By looking at the general results in Table 2, LiDAR values for geometrical characteristics, such as height and width, differs on those obtained with manual measurements that where overestimated. This circumstance was also observed in previous works with this sensor [20, 40]. In the case of the plant height, it is related to the way of taking manual measurements, in which one operator stands with a topographic milestone and other, at a certain distance, must take the measurements by observing the top part of the plants. As this height is important (>2m) and the row spacing is narrow (2 - 2.8 m), the operator might have good skills in read the height value, reading instead its conical projection. In the case of the width, the most external points are taken and, therefore, the measured width for each section is not the mean, but the maximum.

It is very noticeable the fact that mean LWA values for the three GHs are not coincident with the H_M values, having the maximum mean value in GH3 rather than in GH2, which is the one with the highest mean H_M value. At this point the row spacing has more weight on LWA calculation rather than the canopy height. The TRV values, on the other hand, presents similar behavior related to the height and width values variation. In this particular case, data obtained shows that

Due to the height of the canopy is constant (because the structure of the greenhouse) and the row spacing is also determined by the farmer and conditioned by the greenhouse structure, the only parameter that change is the canopy width. For this reason, in this particular case presented on this research, the TRV method seem to be more suitable to determine the amount of canopy instead of LWA, that is mainly affected by the row spacing.

In tomato crop produced in greenhouses the evolution of the LAI is linked to the height of the plant until the plant reaches the top of the greenhouse structure, where the expression of the canopy increases through the width. In this sense, the TRV seems more suitable to describe the vegetation as a result of gives more information across the canopy width rather than LWA, where in this particular case, is most affected by row spacing than canopy height.

n the case of estimating the canopy volumes, given by its TRV, it could be said that the LiDAR methodology is very accurate, for having high determination coefficients, especially when speaking about H_L and V_L. This fact was observed in other crops like vineyards [20], hedgerow fruit trees [46] and big-sized isolated trees, like citrus [47] or olive [40]. Spray application based on the canopy volume has shown to be accurate enough to be considered a first step in the process of the dose adjustment even for very complex canopy structures [11, 48], and it is in this point where lies the importance of having accurate estimating parameters that allow the farmers or technicians to have a very simple criterion to adjust the sprayed volumes, what can be easily done by performing a canopy volume map or by having a sensor operating real time and automatically adjusting the spraying parameters [49].

As to the canopy density, its importance has been deeply suggested by different authors to modify the spray volume calculated with volume-based dosing methods [16, 18, 50]. This parameter can be automatically estimated with the LiDAR scanner, as shown by the significance of the correlations between LAI and H_L and between LAI and V_L. These results are in line with those found in other studies [51] and have a very important repercussion at the time of automatically adjusting the spray dose, as an estimation of the canopy density can be added to the volume estimator for a real-time adjustment of the spray dose, like other authors implemented in other crops [50, 52]. It was surprising for the research team that the LiDAR point number per row length unit was not correlated with canopy density. This fact can have an explanation in the paired planting system, that only allows the laser to scan one plant side and, therefore, did not allow the researchers to properly study the correlation between the LiDAR points and the individual plant's LAD. In further studies, this parameter should be studied from a top perspective in addition to the normal side perspective to check the validity of this parameter.

Speaking about the canopy variation along the row, the LiDAR scanner showed to be a strong methodology to properly characterize all the longitudinal variations in this parameter, and taking into account that it can vary 10 times per meter, as a mean value, manual methods could not afford to manage this high variability. In this sense, the research on mapping methodologies has been very important in last years [30] and further research is necessary to adapt these to the particular case of paired plantation systems in greenhouse tomato crops. The optimal spray volumes should be adjusted to the canopy volume and density as well to transform these volume or density maps in spray volume maps, in order to optimize the spray application process.

Terrestrial 2D-LiDAR sensors can be the most appropriate alternative to characterize the canopy structure for the high accuracy at estimating the canopy volume and density and for their longitudinal resolution, that makes possible have it as a tool to support decisions to adjust the liquid flow rate at a very specific level, allowing the farmers to have their plants protected in an optimum way by preserving them from unnecessary pesticide wastes that affect the environment and their production costs.

5. Conclusions

The canopy characterization with a terrestrial 2D LiDAR scanner was performed in a paired-plantation system in three greenhouse tomato crops and its accuracy was compared with manual characterization methods. The following conclusions can be drawn:

- The LiDAR scanner measurements for the shape parameters of the canopy are highly correlated with the manual measurements. LiDAR generates a certain underestimation of manual values but it can be due to its higher accuracy and the manual methodology limitations.
- Volume parameters, like TRV and LWA can be estimated with the laser scanner with a high statistical significance and high determination coefficients. This point is very important to fit to the new proposals towards dose harmonization according to these parameters in the European Union to ensure the best dose rate adjustments.
- Leaf area index can be estimated by the sensor from the calculated height or volume, but not from the impact number per hedgerow length unit, as expected. Further improvements in the laser scanning process could improve this estimation.
- Canopy variations along a single row are very important to determine the exact input needed in each part of the field and, therefore, manual methods could not fit for having a low longitudinal resolution. LiDAR scanners are able to adapt to this variability, being a very important alternative for the canopy density maps generation.

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Author Contributions:

Jordi Llop and Emilio Gil conceived and designed the experiments; Jordi Llop, Jordi Llorens and Montserrat Gallart performed the experiments; Jordi Llop and Jordi Llorens analyzed the data; Jordi Llop, Emilio Gil and Antonio Miranda-Fuentes wrote the paper; Emilio Gil is the project manager.

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Table 1. Main characteristics of the experimental fields.

Greenhouse ID	**Location**	**Plant layout** (row spacing x plant spacing) *(m x m)*	**Crop**
1	El Ejido (Almería)	2.5 x 0.4	*Solanum lycopersicum* L. cv. Velasco
2	El Ejido (Almería)	2.8 x 0.4	*Solanum lycopersicum* L. cv. Velasco
3	Viladecans (Barcelona)	2.0 x 0.4	*Solanum lycopersicum* L. cv. Barbastro

Table 2. Geometrical and density values for all the measured and calculated parameters.

	Parameter		**Greenhouse ID**		
			1	**2**	**3**
Manual characterization	**Manual height**	**H_M** (m)	2.19 ± 0.02	2.50 ± 0.02	1.96 ± 0.04
	Manual width	**W_M** (m)	0.62 ± 0.02	0.43 ± 0.04	0.53 ± 0.01
	Tree Row Volume	**TRV** (m^3 ha^{-1})	10882 ± 397	7711 ± 212	10397 ± 252
	Leaf Wall Area	**LWA** (m^2 ha^{-1})	35111 ± 360	35683 ± 290	39170 ± 755
	Leaf Area Density	**LAD** (m^2 m^{-3})	5.81 ± 0.28	3.15 ± 0.15	5.30 ± 0.19
Electronic characterization	**LiDAR Height**	**H_L** (m)	1.90 ± 0.07	2.12 ± 0.01	1.93 ± 0.03
	LiDAR Width	**W_L** (m)	0.71 ± 0.02	0.64 ± 0.02	0.59 ± 0.03
	LiDAR volume	**V_L** (m^3)	1.13 ± 0.07	1.32 ± 0.03	2.42 ± 0.12

Table 3. All possible comparisons among all the measured and calculated parameters related to the canopy volume and density.

			Manual measurements						**LiDAR measurements**			
			H_M (m)	**W_M** (m)	**LAI** ($m^2\ m^{-2}$)	**TRV** ($m^3\ ha^{-1}$)	**LWA** ($m^2\ ha^{-1}$)	**LAD** ($m^2\ m^{-3}$)	**IMP** (m^{-1})	**H_L** (m)	**W_L** (m)	**V_L** (m^3)
Manual	**H_M**	(m)	1	0.29**	0.60**	0.50**	0.21*	0.53**	0.20*	0.59**	0.003	0.69**
	W_M	(m)		1	0.70**	0.86**	0.01	0.65**	0.20*	0.52**	0.10	0.16
	LAI	($m^2\ m^{-2}$)			1	0.89**	0.02	0.97**	0.01	0.52**	0.01	0.36**
	TRV	($m^3\ ha^{-1}$)				1	0.08	0.79**	0.03	0.46**	0.01	0.37**
	LWA	($m^2\ ha^{-1}$)					1	0.01	0.51**	0.004	0.29**	0.33**
	LAD	($m^2\ m^{-3}$)						1	0.01	0.47**	0.01	0.32**
LiDAR	**IMP**	(m^{-1})							1	0.0001	0.17	0.27*
	H_L	(m)								1	0.10	0.31**
	W_L	(m)									1	0.03
	V_L	(m^3)										1

Selection criteria: * interesting relationship; ** good correlation is expected

Figure captions

Figure 1. (**a**) Twin plantation system; (**b**) Plant disposition inside the greenhouse, with row spacing, *rs*, plant spacing in a row, *ps*, and twin plant spacing, *tps*.

Figure 2. Measured parameters for the manual canopy characterization and LiDAR scanner disposition.

Figure 3. (**a**) Fixed structure of the LiDAR support system for measurements in greenhouses 1 and 2. (**b**) LiDAR scanner mounted on a radio control mobile platform for measurements in greenhouse 3.

Figure 4. (**a**) LiDAR points cloud in CloudCompare ® software with coordinate system and canopy delimitation procedure. (**b**) Plant delimitation process (three cases).

Figure 5. Linear correlations between (**a**) LAI and VL, and (**b**) LAI and TRV

Figure 6. Calculated LAI variation along the scanned row in GH3.