Development of a portable system for detection of leaf area in plants

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Abstract: Recently, the determination of leaf area and growth rates in plants through portable devices has become popular, due to the advantages offered by artificial vision systems to identify and classify objects using image processing. The purpose of the research was to develop a portable system by mobile device for measuring leaf area through image recognition. The methodology includes 3D designs, acrylic device building, determining the area in pixels by the technique of radial basis neural networks (RBFN) directly in the RGB color space and pixel conversion to cm^2. The results obtained by analysis of variance for each species showed that the p-value was greater than 0.86 for each class of plants. Moreover, the system obtained coefficients of determination higher to 0.90, 0.95 y 0.99 for leaves of orange, patevaca and chirimoya respectively, from a set of 30 leaves belonging to three species of plants with different sizes and areas compared to manual analysis. This system is a useful tool for the objective determination of leaf area in plants and becomes a nationwide alternative compared to existing expensive systems. Furthermore, the system is reprogrammable, flexible, not destructive and low cost.

Keywords: leaf area, artificial vision system, mobile device, radial basis neural networks, image processing

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1 Introduction

Nowadays, fruit production and demand has increased due to favorable weather conditions present in tropical countries like Colombia (Ministry of environment, housing and territorial development, 2016); however, the supply of fruit depends on their quality and the conditions in which crops are, caused by global climate change (GreenFacts, 2016).

Recently, there have been advances in systems for determining leaf area in plants, such a case of using a known reference to determine the leaf area without depending on the camera position (Hajjdiab and Obaid, 2010; Easlon and Bloom, 2014). Likewise, there have been systems where conventional techniques that have high rates of correlation are used with respect to an expert, like by Shivling et al.(2011) or by default, where it is used learning algorithms for leaf sorting, as described by Wang et al.(2012); Sharma and Gupta (2015). Finally, there have been developed mobile applications such as App PocketLAI, being the pioneer in the estimation of leaf area rate for Smartphone (Confalonieri et al., 2013; Vesali et al., 2015).

To date in Colombia, this process is manually performed in a destructive form, which involves taking a sample of the leaf with an area of 1 cm^2; then identify its weight through a precision weighing scale, resulting in a linearity between the weight and area (g/cm^2); and then get the approximate measurement of the total leaf area through a direct rule of three.

This method has problems such as imprecision in the measurements, which leads to the destruction of crops and abnormal plant growth because they don't have the ability to capture the active photosynthetic radiation

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(Kozlowski et al., 1991). The purpose of this research was to develop a portable system to determine the leaf area of plants through artificial vision systems objectively and without destroying the plant.

The proposed methodology consisted in the application of computer vision techniques, which are composed of different methods of image and video processing, such as methodologies for image acquisition, implementation of filtering operations, object segmentation through radial basis functions directly in the RGB color space, and others. Finally, the mobile device identifies the leaf area in the leaves on images.

2 Materials and methods

In the project development, the process for leaf area detection in plants using image processing and mobile systems was described. The following describes each of the steps of the process, as evidenced in Figure 1.

At a first instance, 3D designs were developed using software Solid Works 2013 from the analysis of user requirements and restrictions. Later, each of the parts were assembled and were implemented the algorithms for image acquisition and processing through mobile device. The methodology proposes the identification the foliar area on plants, through image processing techniques compatible with the android 5.0 operating system and implemented on mobile devices such as tablets or Smartphone, for this particular research was used the Samsung Galaxy Tab Tablet with memory 3 GB of RAM and Octa-Core processor at 1.9 GHz. In first step, the focus of the image was made using the auto focus function available in the camera application and the camera lens was adjusted with an exposure value of 2.0 for capturing images, then the filtering step was applied by median filter 3×3 to reduce the abrupt changes in pixel intensity. The criterion of radial basis neural functions (RBNF) was applied (Lopéz and Consularo, 2005) to identify objects in the image. Finally, the leaf area was determined by a direct ratio between pixel quantity and centimeters, rapidly, objectively and with repeatability in the plant physiology analysis.

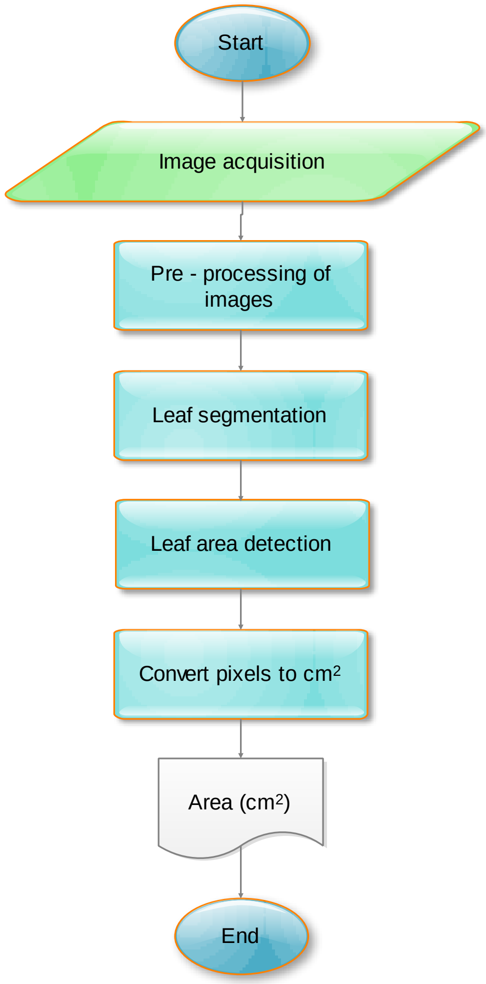
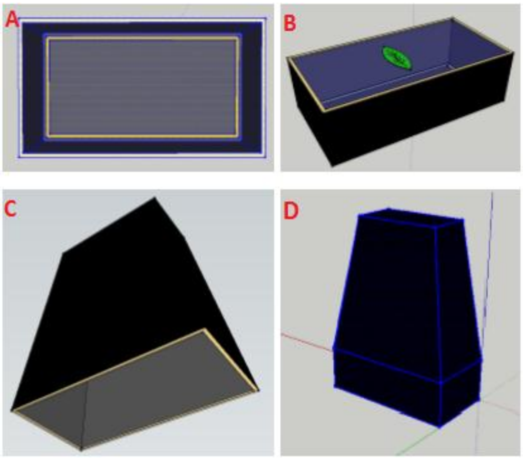


Figure 1 Proposed methodology

2.1 Design of portable system

For the project development, it was taken into account the restrictions and requirements demanded by experts in plant physiology from University of Cundinamarca, where a prototype called leaf detector was set to measure leaf area in plants with a maximum leaf size of 15cm × 30cm, portable, non-destructive and programmable, with controlled parameters of illumination.

The used material for making the portable device was acrylic, due to the physical characteristics it possesses, such as resistance to water and sunlight. In addition, its construction in lightweight material makes it possible the mobilization in all circumstances. For this, it was taken into account 5mm of thickness throughout the prototype. Likewise, the hardware design for the module (leaf detector) was constructed cone shaped in order to reduce weight and space; also it has a height of 30cm to locate the light sources stage internally and to adapt the space needed by the camera to capture leaf images properly.



A. Overhead view. B. Side view showing support glass. C. Diagonal view. D. Lateral view of the whole device.

Figure 2 3D module design (*leaf detector)*

Moreover, the image acquisition step in the central part of the module was conditioned. It is worth noting that the device was made in black, so that certain external factors such as natural light cannot affect capture and image acquisition directly on plantations, then Figure 2 shows the module design in Solid Works 2013.

2.2 Image acquisition and pre-processing

The image acquisition stage for the module (leaf detector) was based on a graphical interface on Android system, which complies with the following features: user authentication, image capture, image storage, image removal, leaf area calculation in a controlled manner, leaf area calculation with a square of reference, measurement registration and consultation of measurements made. For this module the image was captured with a Samsung Galaxy S Tablet with the following characteristics: Main camera 8 MP CMOS, screen resolution of 2560 × 1600 (WQXGA), screen size (8.4 "(212.8mm)), Octa-Core processor 1.9GHz, 1.3GHz, 3GB RAM, internal (16GB) and external Micro SD (up to 128GB) Android operating system, physical dimensions (212.8 height × 125.6 width × 6.6 depth), weight of 294 g, which capture images wirelessly with 16 Mpx resolution and an aspect ratio of 16:9 in JPG format. Later, it was fragmented into its three RGB color components for filtering each one using a median filter (Alfaro, 2014).This filter allows to attenuate the noise on images and usually it is applied to grayscale images.

2.3 Image segmentation

For the leaf extraction by the module (leaf detector) the method of radial basis functions network (RBFN) was implemented (Lopéz and Consularo, 2005) which consists of comparing image values in the RGB color spectrum through a distance in color space to a determined point (Xu and Wunsch, 2010), using Equation 1:

$$D(i,j) = \sqrt{(ima(i,j,1) - px(1))^2 + (ima(i,j,2) - px(2))^2 + (ima(i,j,3) - px(3))^2} \qquad (1)$$

Where: *ima* is the original image in each of its color components and *px* is the reference pixel for each color components. Then, each of the distances found is evaluated by the Gaussian function shown in Equation 2.

$$E(i,j) = e^{-\frac{D(i,j)}{255}} \qquad (2)$$

Finally, pixels belonging to the leaf are extracted and assigned in white if it exceeds an estimated percentage and others are assigned in black color.

2.4 Leaf area detection

The leaf area detection stage was conducted in two ways to the module (leaf detector): with reference and without known reference. In the case where there was not a known reference the process was based on counting the number of white pixels belonging to the leaf area and multiplied by a factor as is shown in Equation 3 and for the case that there was a known reference, the process was based on counting the number of pixels of the object and multiplied by a factor as is shown in Equation 4.

$$Area(cm^2) = \frac{\#\, rows * \# columns}{axis\ x\ (cm) * axis\ y\ (cm)} * (pixel\ area) \qquad (3)$$

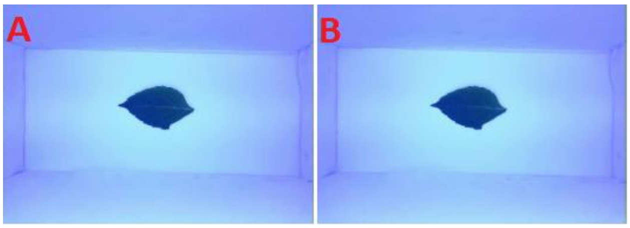
$$Area(cm^2) = \frac{\#\, leaf\ pixels}{\#\, reference\ pixels} * reference(cm^2) \quad (4)$$

3 Results and discussion

In order to standardize a methodology for identification of leaf area in plants by mobile devices and prior to the development of the algorithm, design and assembly of the portable system (leaf detector) was realized for determining the leaf area. Figure 3 shows the results with Solid Works design of the portable device.

Figure 3 Module construction *(leaf detector)*

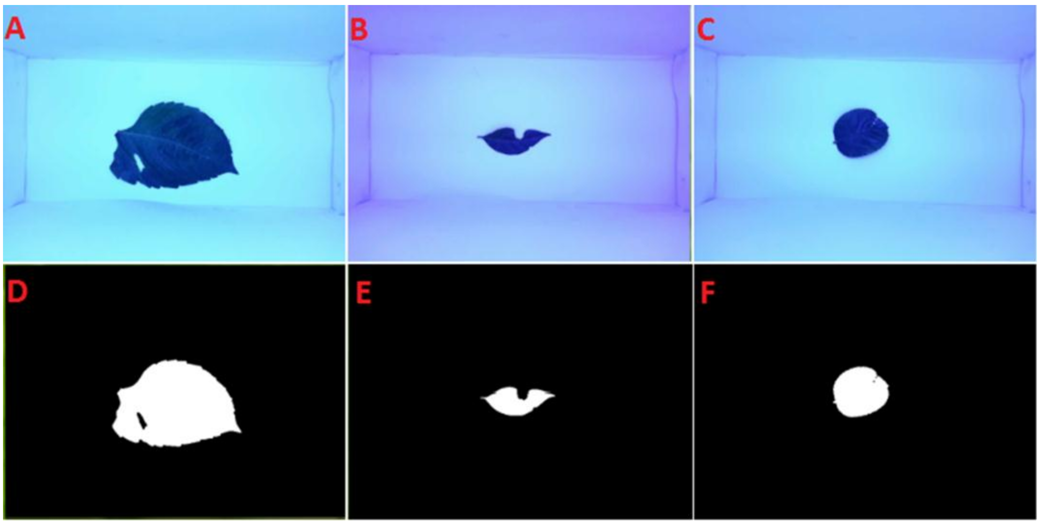
The first stage tested was the process of image acquisition and pre-processing, to get the leaf area easily without distortions that affect the measurement. For which, the performance of three different filters was evaluated in test images obtained with the system (leaf detector), comparing the filters' performance. It was found that the median filter showed better results in terms of preserving the edges and decrease of abrupt variations in pixel intensities in the images.



A. Original image B. Filtered image

Figure 4 Image acquisition

In Figures 4A and 4B, the results of the image acquisition and pre-processing are shown respectively. Later, the extraction stage of the regions belonging to the leaf was evaluated. Through the system (leaf detector), radial basis neural networks were applied to extract the region of the leaf and the results were satisfactory compared with other traditional methods of segmentation, because neural networks allowed to segment directly in the RGB space color. Then in Figures 5A, 5B and 5C original leaf images with holes and damaged edges are shown and in Figures 5D, 5E and 5F the results of the segmentation process are illustrated by the portable system (leaf detector), showing very good results in which no relevant leaf information is lost even when this has holes or other abnormalities as evidenced in Figures 5E and 5F respectively.



A. Leaf with hole B. Leaf with damaged edge C. Complete leaf D. Segmentation of leaf with hole E. Segmentation of leaf with damaged edge F. Segmentation of complete leaf

Figure 5 Image segmentation process

Finally, the identification stage of leaf area was tested and was determined by a ratio of pixel quantity to centimeters as is shown in Equations 3 and 4. Subsequently, a graphical interface for displaying results was implemented as evidenced in Figures 6 and 7, showing different leaves with good results. It is also easy to be handled for users.

Figure 6 Graphical interface of portable system (Leaf 1).

Figure 7 Graphical interface of portable system (Leaf 2).

To validate the proposed portable system, the analysis of leaf area for three different plant species with ten leaves each with different sizes, holes and damaged areas was performed, in order to determine the system accuracy (leaf detector) with known reference and without reference in such situations where the leaf has different conditions with respect to the manual method and the precision weighing scale by the expert in agronomy currently used in University of Cundinamarca.

Initially, the statistical validation was performed on the software InfoStat, which allowed to evidence that for Orange leaves the developed system showed high correlation with a p-value of 0.8704 exceeding the limit of 0.05 with respect to conventional methods. In addition, it was verified by Tukey significance test that the measurements of leaf area showed no significant differences and remained in the same class A, as evidenced in Figure 7.

Cuadro de Análisis de la Varianza (SC tipo III)

F.V.	SC	gl	CM	F	p-valor
Modelo.	38,79	3	12,93	0,24	0,8704
Metodos	38,79	3	12,93	0,24	0,8704
Error	1969,05	36	54,70		
Total	2007,85	39			

Test:Tukey Alfa=0,05 DMS=8,90770

Error: 54,6960 gl: 36

Metodos	Medias	n	E.E.	
Balanza	31,76	10	2,34	A
LD	31,99	10	2,34	A
Manual	32,70	10	2,34	A
LDP	34,28	10	2,34	A

Medias con una letra común no son significativamente diferentes (p > 0,05)

Figure 7 Statistical results for Orange leaves using software InfoStat

Subsequently, for Patevaca leaves, the software InfoStat allowed to prove that the developed system showed high correlation with a p-value of 0.9973 exceeding the limit of 0.05 with respect to conventional methods. It was also verified by Tukey significance test that measurements of leaf area showed no significant differences and remained in the same class A, as is shown in Figure 8.

Cuadro de Análisis de la Varianza (SC tipo III)

F.V.	SC	gl	CM	F	p-valor
Modelo.	11,78	3	3,93	0,02	0,9973
Metodos	11,78	3	3,93	0,02	0,9973
Error	9107,37	36	252,98		
Total	9119,15	39			

Test:Tukey Alfa=0,05 DMS=19,15726

Error: 252,9826 gl: 36

Metodos	Medias	n	E.E.	
Manual	81,13	10	5,03	A
Balanza	82,22	10	5,03	A
LDP	82,37	10	5,03	A
LD	82,50	10	5,03	A

Medias con una letra común no son significativamente diferentes (p > 0,05)

Figure 8 Statistical results for Patevaca leaves using software InfoStat.

Finally, for Chirimoya leaves the system showed high correlation with a P-value of 0.7561 exceeding the limit of 0.05. And it was verified by Tukey test that leaf area measurements showed no significant differences and remained in the same class A, as is shown in Figure 9.

Cuadro de Análisis de la Varianza (SC tipo III)

F.V.	SC	gl	CM	F	p-valor
Modelo.	587,67	3	195,89	0,40	0,7561
Metodos	587,67	3	195,89	0,40	0,7561
Error	17771,53	36	493,65		
Total	18359,20	39			

Test:Tukey Alfa=0,05 DMS=26,76080

Error: 493,6535 gl: 36

Metodos	Medias	n	E.E.	
Balanza	53,37	10	7,03	A
Manual	58,03	10	7,03	A
LD	59,12	10	7,03	A
LDP	64,15	10	7,03	A

Medias con una letra común no son significativamente diferentes (p > 0,05)

Figure 9 Statistical results for Chirimoya leaves using software InfoStat.

On the other hand, an analysis of correlation between manual measurement by the expert with respect to the portable system with and without reference was performed. It was found that coefficients of determination more than 0.90 for Orange leaves, more than 0.95 for Patevaca leaves and more than 0.99 for Chirimoya leaves. Below, the results without reference (LD) and known reference (LDP) are shown by Figures 10, 11, 12, l3, 14 and 15 respectively.

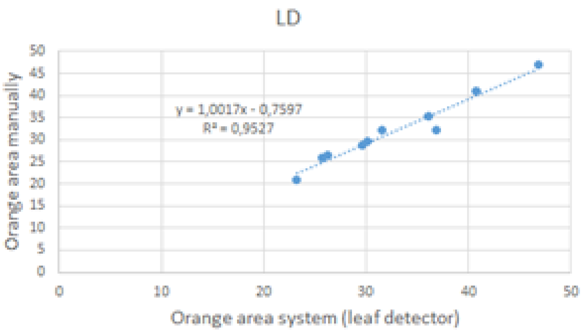


Figure 10 Correlation for Orange leaves

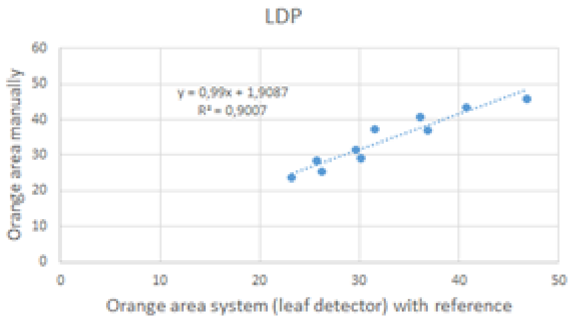


Figure 11 Correlation for Orange leaves with reference

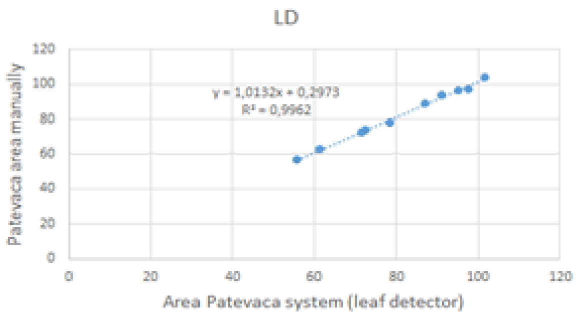


Figure 12 Correlation for Patevaca leaves

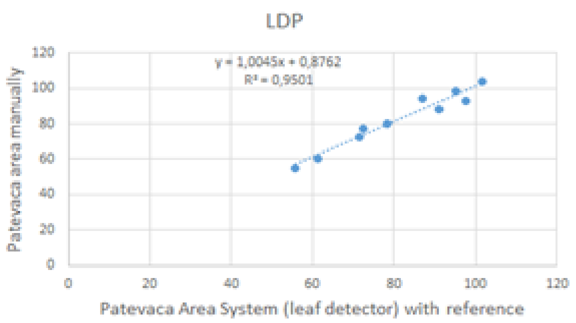


Figure 13 Correlation for Orange leaves with reference

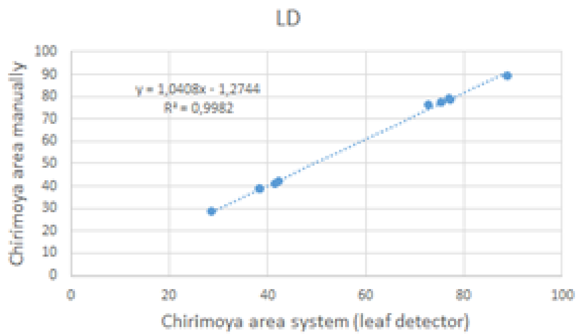


Figure 14 Correlation for Chirimoya leaves

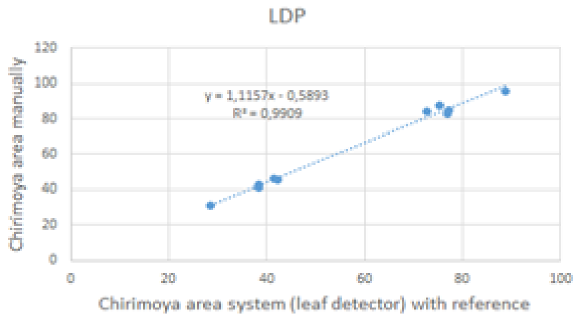


Figure 15 Correlation for Chirimoya leaves with reference

Subsequently, the statistical correlations for the system (leaf detector) without reference and known reference regarding the manual method and the method of the precision weighing scale were performed, as is shown in Figures 16, 17 and 18 for each plant species.

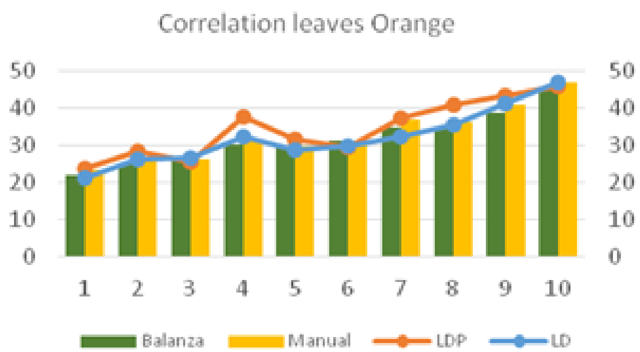


Figure 16 Correlation between *Leaf detector* (LD and LDP) regarding to manual method for Orange leaves

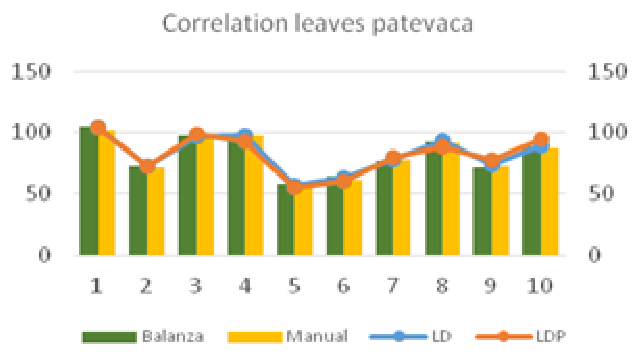


Figure 17 Correlation between *Leaf detector* (LD and LDP) regarding to manual method for Patevaca leaves

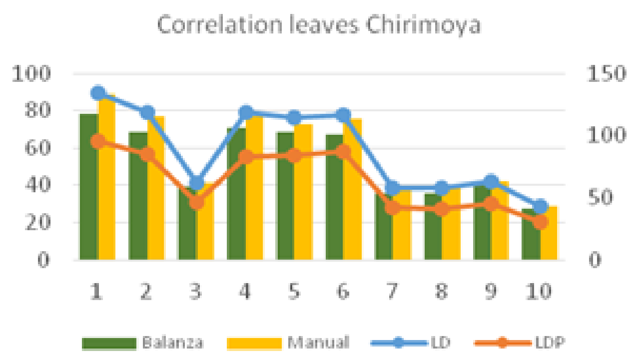


Figure 18 Correlation between *Leaf detector* (LD and LDP) regarding to manual method for Chirimoya leaves

The results obtained with the system (leaf detector) show in figures 10 to 15, determination coefficients higher than 0.9 for orange tree leaves, patevaca tree leaves and chirimoya tree leaves, indicating a high degree of accuracy with respect to the reference method (manual). Likewise, the results obtained with respect to the scale precision and the manual reference method were compared in Figures 16, 17 and 18 and the trend was maintained for the 10 leaves in each plant species, allowing the obtaining of reliable measurements for the leaf area.

Finally, the obtained results of the system (Leaf detector) with respect to the manual method where validated through the Bland-Altman verification test and no significant variability was found between the measured leaf area assigned by the expert and the portable system. The results show a ratio of 0.96 in a confidence interval of 95% (-3.9 to 2.5) for Orange tree leaves. Also, they show a ratio of 0.99 in a confidence interval of 95% (-0.61 to 3.35) for Patevaca tree leaves and a ratio of 0.96 in a confidence interval of 95% (-1.49 to 3.67) for Chirimoya tree leaves as is shown in Figures 19 to 21 respectively.

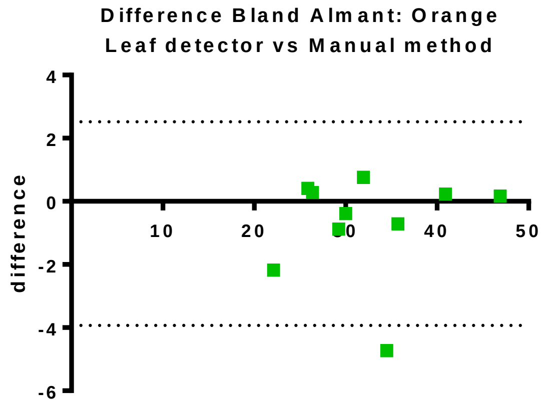


Figure 19 Bland-Altman test for Orange leaves

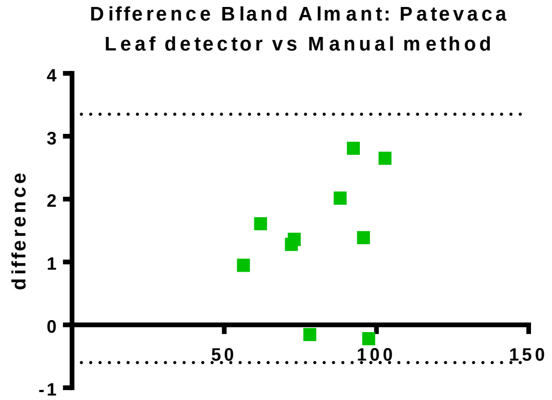


Figure 20 Bland-Altman test for Patevaca leaves

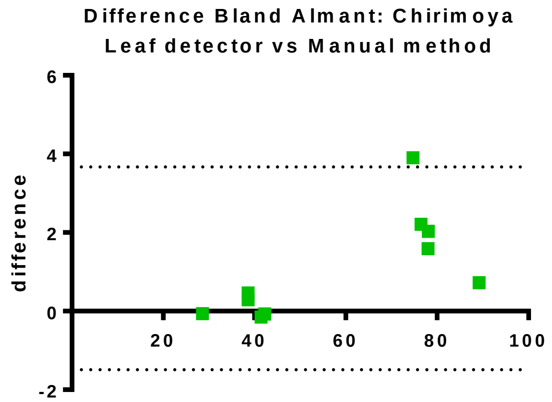


Figure 21 Bland-Altman test for Chirimoya leaves

The results with the concordance test Bland-Altman between two measurement methods showed that the portable system presented high correlation indices compared to the method (manual), in Figures 19, 20 and 21 was evidence that difference between measurements were not significant because the differences remained within the confidence interval of 95%, obtaining a solution to problems of accuracy in plant growth analysis. Finally, the precision of the results and characteristics of the developed system was compared with regard to current portable systems as shown in Table 1. The proposed system was implemented in free software as solution to low cost, obtaining accuracy percentages greater than 90% in measurements leaf area similar to current studies and avoiding the destruction of the plant.

Table 1 Comparison between portable systems and mobile applications for leaf area identification

Technique	Features	Results
Proposed system	Leaf area identification using image processing on mobile devices, non-destructive and low cost	Range of (90% to 99%) for three plant species
(Hajjdiab and Obaid, 2010)	Leaf area detection using artificial vision, destructive and low cost	Error of 1% in measurements for one plant specie
(Easlon and Bloom, 2014)	Artificial vision system using ImageJ platform, destructive and low cost	Error of 1,67% for different plant species
(Easlon and Bloom, 2014)	Novel method for leaf area detection using an scanner, non-destructive and moderate cost	Correlation of 99% regarding to Li-Cor 3100 measurements.
(Sharma and Gupta, 2015)	Recognition system for different plant species using neural networks, destructive and low cost	Accuracy of 91.13% when sorting 16 different leaf species.
(Confalonieri, et al, 2013)	Mobile application App PocketLAI for leaf area index estimation, non-destructive, ability to capture images up to 57 tilt degrees and high cost	Accuracy of 96% for a single plant species regarding to destructive methods-
(Vesali, Omid, Kaleita, and Mobli, 2015)	Mobile application S-SPAD for estimation of chlorophyll content in corn leaves, non-destructive and moderate cost	Linear relation of R=0.57 and high sensibility.
(Campos-Taberner, et al, 2015)	Mobile application App PocketLAI and LAI-2000 for leaf area index estimation, non-destructive and high cost	Accuracy of 94% and 95% for a single plant species, respectively

4 Conclusions

In this article, the development of a portable system is shown based on techniques of digital image processing on mobile devices for determining the leaf area in plants with known reference and without it, which has the advantage of adaptability for the determination of other parameters shown on leaves, as abnormalities or nutritional deficiencies, among others.

The results were validated by variance analysis in which a p-value of 0.8704 for Orange leaves, a p-value of 0.9973 for Patevaca leaves and a p-value of 0.7561 for Chirimoya were obtained using Tukey test present in InfoStat software. This test showed that for the three kinds of plants the p-value was greater than 0.05, indicating the similarity in portable measurement system with respect to manual method.

The proposed system allowed determining the leaf area in plants in two ways: by known reference and without reference with high accuracy compared with conventional methods used in Universidad de Cundinamarca by technical experts. The system obtained coefficients of determination greater than 0.90 with known reference and 0.9527 without reference to Orange leaves, coefficients of determination greater than 0.95 with known reference and 0.9962 without reference for Patevaca leaves and coefficients of determination greater than 0.99 with known reference and 0.9982 without reference for Chirimoya leaves, denoting good performance by the portable system.

Through Bland-Altman validation, it was found that the portable system (Leaf detector) did not show significant variability with respect to the results obtained by experts in plant physiology, with significance ratios greater than 0.96 in a confidence interval of 95% for all the three plant species. For this reason, the system is a useful tool for the objective determination of leaf area in plants and presents an alternative at a national level for the existing expensive systems for leaf area parameters detection.

Future researching work will focus on identifying growth rates for plants in normal and severe conditions, like plants that have leaves with holes in his body, edge deformity and partially damaged. As well as, the adaptability and application of our portable system in other similar fields such as detection of nutritional deficiencies, among others.

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