Interpretation of Chlorophyll Indexes to Estimate the Health Status of Plants within a Polyculture Model Implemented in the Municipality of Ponedera, Atlántico (Colombia), Using Multispectral Images

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***Abstract*—Multispectral surveys enable information collection from fertile soils using unmanned aerial vehicles equipped with cameras capable of capturing images in specific narrow ranges of visible and non-visible light spectra. The research presented in this article focuses on identifying various variables such as plant health, chlorophyll levels, and the presence of desired nutrients. These variables are assessed using the Chlorophyll Index (CI) through the development of an inspection and monitoring strategy, which allows for the rapid characterization of the soil under study and facilitates decision-making in agricultural activities. The strategy was implemented on a specific property in Ponedera, Atlántico (Colombia), where a polyculture of beans, plantains, and cassava was cultivated. The study involved conducting multispectral surveys at multiple time points for three months.**

***Keywords*—chlorophyll index, multispectral images, polycultures, soil characterization**

I. Introduction

The utilization of new technologies in agricultural practices is a significant challenge faced by the rural areas of Colombia [1]. The inclusion of remote monitoring tools [2] has emerged as a valuable source of information, aiding in increasing production while reducing the need for resources such as fertilizers and pesticides [3, 4] and promoting the efficient use of available water resources [5].

One of the most common tools for remote monitoring of plant health is the analysis of the Chlorophyll Index (CI), widely used to calculate the total amount of chlorophyll in plants [6]. In other words, CI serves as a relatively accurate indicator of plant health because it measures the spectral reflectance of chlorophyll, crop conditions can be monitored regularly. Plants depend on chlorophyll to survive since they absorb sunlight, which is later converted into sugars and starches through photosynthesis, making this index an effective tool for managing nutrients during crop growth.

It is essential to thoroughly understand the subject matter regarding the aforementioned tool, starting with the basic concept of electromagnetic wave behavior and their interaction with objects [7], which for this particular work, refers to the incidence of these waves on plant leaves and how they are reflected or absorbed. From there, acquiring multispectral images emerges and how they can be applied as a valuable technology to identify the phenological characteristics of crops or productive soils [8].

The concept of precision agriculture [9] emerged from the initiative to design and implement ideas that enable the use of resources and the development of sustainable agriculture without detracting from production behavior [10]. These ideas revolve around a mobility platform based on unmanned aerial vehicles, guaranteeing non-invasive monitoring and remote sensing of the most general characteristics of analyzed crops, making visible what may be imperceptible to the naked eye [11].

The technology for monitoring plant health through remote sensing described above was implemented in six municipalities in the Department of Atlántico as part of the project “strengthening innovation processes in agricultural production that improve the sustainability

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and food security of peasant families in the Department of Atlántico".

One of the project's objectives was to develop agricultural models and practices aimed to use technologies that improve agricultural systems. This involved establishing models based on the implementation of sustainable agriculture, incorporating techniques such as biofertilization and the use of hydroretainers (efficient use of water).

Each of these models underwent monitoring and tracking of biotic and abiotic factors, including climatic conditions, among others, which could affect plant growth and development, using a series of analyses that included the use and interpretation of chlorophyll indices through multispectral images. For each of the properties in the different municipalities, images were acquired in different light spectra, which were subsequently processed and analyzed, thus providing timely information on the health status of the plants.

This article refers to a particular property in the municipality of Ponedera, where an agro ecological model was implemented for the polyculture of beans, plantains, and cassava. To achieve success in the strategy, a methodology of multispectral surveys was defined at regular intervals (three in total) within a one-month observation window between each overflight, guaranteeing an adequate monitoring and comparison process of the evolution of coverage, as well as the phytosanitary status of the plants.

II. METHODOLOGY

Multiple methodologies that allow for the optimal implementation of this type of monitoring technology, not only acquiring images in different light spectra but also RGB images [12], which can obtain contour lines and high-quality images with metadata regarding global positioning at the time they were acquired [13]. Different types of sensors are available in the international market that stand out for the quality of the images they acquire [14]. Remote monitoring using earth observation satellites is also extensively used in agriculture [15, 16].

In this research, a series of activities were developed to carry out a successful multispectral survey [17]. The collected information generated orthophotomosaics, consolidating all the images acquired per property. The same methodology was followed for all properties.

Regarding the initial activities for project development, geographical numerical data were collected from the land hectares under study, using the Magna Bogotá reference system to generate flight plans to be followed by the unmanned aerial vehicle under autonomous flight mode [18]. The aerial vehicle has a sensor capable of perceiving electromagnetic radiation with different wavelengths, specifically highlighting five spectral bands: red, green, blue, near-infrared, and red edge [19, 20]. The sensor was selected considering the number of available bands, weight, and the ability to store information in a high-speed writing SD memory, which discards the possibility of image loss. The camera had a resolution of 8 cm per pixel at 120 m altitude with capture speeds of up to 1 capture per second.

The image acquisition process began by establishing polygon points corresponding to the limits of the land to be sampled, visually inspecting the physical properties of the terrain, and identifying possible obstacles that the unmanned aerial vehicle may face in order to prevent accidents. The global positioning system points are acquired through real-time satellite kinetic navigation equipment, obtaining high accuracy in the acquired positioning.

Once the polygons are defined, flight plans are created, configuring, among other things, the altitude at which the image acquisition will be performed, setting the parameter between 100 m and 120 m and flight speed. The vehicle executes the flight plan under the supervision of the pilot in charge of the aircraft in case intervention is necessary for any maneuver (see Figs. 1 and 2).

Fig. 1. Flight plan. Source: Authors.

Fig. 2. Drone with a multispectral camera. Source: Authors.

For image processing, photometry software that allows the manipulation of RGB and multispectral images is required. Pix4D software was used on this occasion, which enabling capturing images with any camera, transforming images into digital models, generating quality reports and calibration details, measuring distances, areas, and volumes, and extracting elevation profile data. Moreover, it allows for calculating different vegetation indices, including the chlorophyll index CI, the selected index for this research.

Once multispectral orthophotomosaics are obtained for each location, the images are presented with proper georeferencing. The results of the percentage of covered areas are categorized into four intervals, and the condensed chlorophyll indices are organized in a table, grouped by property. Then, the respective analysis of each image per overflight was carried out, presenting the information in a disaggregated and comprehensible manner. This allows the farmer and their advisors to make timely decisions regarding the measures to be implemented based on the established agro ecological model within the property.

It should be noted that in the implemented strategy, a methodology of multispectral surveys was defined at specific intervals (three in total) within a one-month observation window between each overflight to ensure a comparison process between one moment and another, evaluating the evolution and behavior of coverage percentages, as well as the phytosanitary state of the plant material.

After the processing and analysis of the spectral images obtained during the project, visits to the polyculture by the owner and trained personnel in pest and disease identification were carried out to corroborate the data obtained through the images and define an interval for the interpretation of the results obtained through the multispectral survey.

Tools like the PIX4D application are highly comprehensive due to their ability to perform volume, area, and elevation calculations and provide the capability for versatile virtual inspections. Such software greatly facilitates the processing of multispectral images for generating spectral maps and calculating chlorophyll indices. Successfully processing of all this information depends on factors such as sensor calibration before each flight, proper organization of collected data storage, and appropriate technical knowledge. Depending on the complexity and the number of images to process, this can lead to a significant computational cost, requiring not only the use of such software but also high-end computers with powerful processors of up to eight cores and a minimum of 16 GB RAM to expedite information processing as quickly as possible.

A. Survey and Analysis of the First Aerial Flyover

The first multispectral survey was carried out on a previously selected property in the municipality of Ponedera, located in the department of Atlántico, with the aim of identifying the types of coverage present in the study area, taking as a variable the percentage of area of the same according to the levels of chlorophyll present and the phytosanitary status of the vegetal material, which in this case of study was in a polyculture of beans, plantain, and cassava. Fig. 3 shows an orthomosaic image of the corresponding area of the property.

Once the aerial information of the property was extracted, the corresponding multispectral orthomosaic was obtained, providing information on chlorophyll indices through the color palette, as shown in Fig. 4.

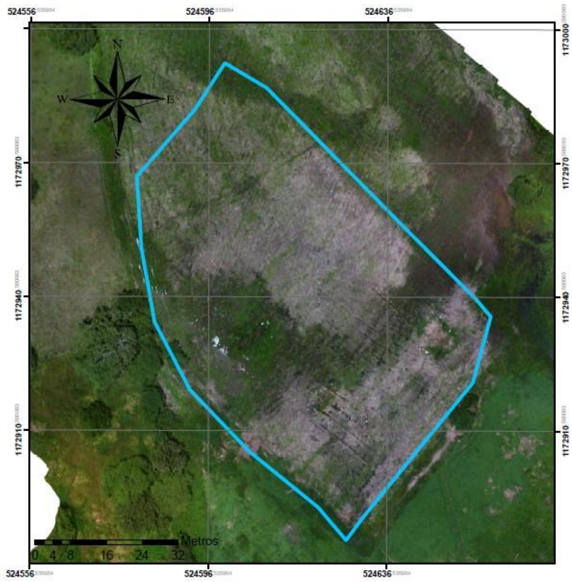

Fig. 3. Orthomosaic of the property. Source: Authors.

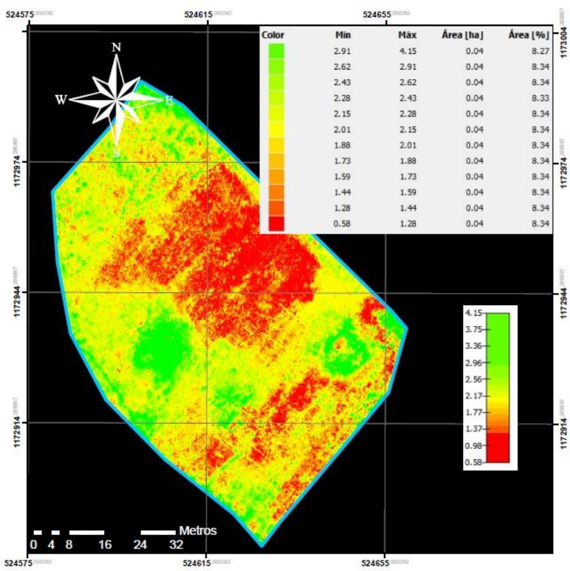

Fig. 4. Multispectral Orthomosaic of the chlorophyll index of the property. Source: Authors.

With the information obtained and its interpretation, the data was categorized into four intervals: healthy vegetation, Moderately healthy (Mh) vegetation, sick vegetation, and zero vegetation cover that characterizes the chlorophyll indices. Healthy vegetation was determined for values equal to or greater than 3.1, moderately healthy vegetation between 1.71 and 3.1, sick vegetation between 0 and 1.71, and zero vegetation cover for values less than zero, as shown in Table I.

TABLE I. CLASSIFICATION OF CI INTERVALS OF THE PROPERTY

Category	Interval		Area (%) 1st overflight
	Min	Max	
Healthy vegetation	3.10	>3.10	8.27
Mh vegetation	1.71	3.10	58.37
Sick vegetation	0.00	1.71	33.36
Zero vegetation cover	<0.00	0.00	0.00

Source: Authors

Analyzing the results obtained, it can be obtained that in 8.27% of the study area, due to its reflectance, a higher number of vegetal cells are present, indicating an increased presence of chlorophyll in the plant, which is an indicator of a healthy state of the plants with the desired nutrient presence or, in other words, a low presence of nutritional deficiencies in the plant. Similarly, the study area presents 91.73% that can be associated with low levels of chlorophyll, therefore, in these areas, efforts were required to improve their nutritional conditions or to review the presence of some type of pathogen or species that affects growth or health status. In these areas, it was necessary to monitor the photosynthetic activity of the plants to prevent them from decreasing prematurely prior to the planting process.

Once the spectral survey of the first flyover and the corresponding analysis based on the interpretation of chlorophyll index values and their respective contributions, a second survey was carried out with a difference of one-month interval between the two flyovers. This was done to proceed with the comparative analysis between the two flyovers based on the distribution behavior of the percentage area according to the Chlorophyll Indices (CI) present.

B. Second Spectral Survey

As mentioned, a second multispectral survey was carried out on the same property one-month after the first flyover. The objective was to identify the health status of the coverages in the study area, considering the percentage of the area as a variable.

Figs. 5 and 6 show the property's RGB and multispectral orthomosaics during the second flyover. Similarly, the property's chlorophyll index intervals were classified, and distributed in the four characteristic intervals, as shown in Table II.

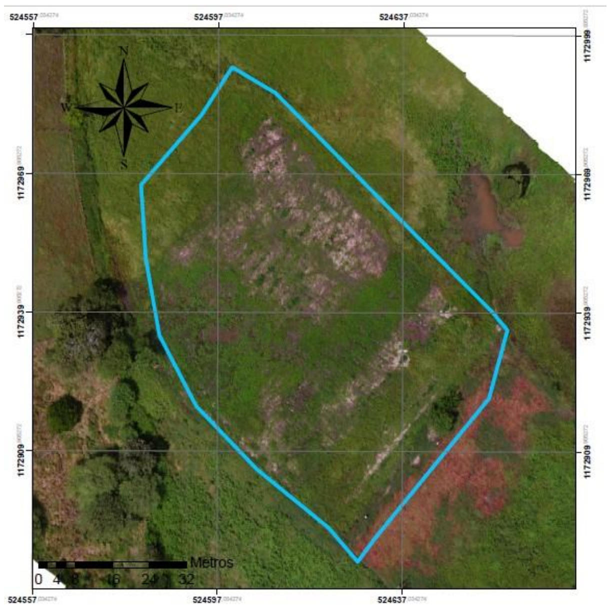

Fig. 5. Orthomosaic of the property in its second survey. Source: Authors.

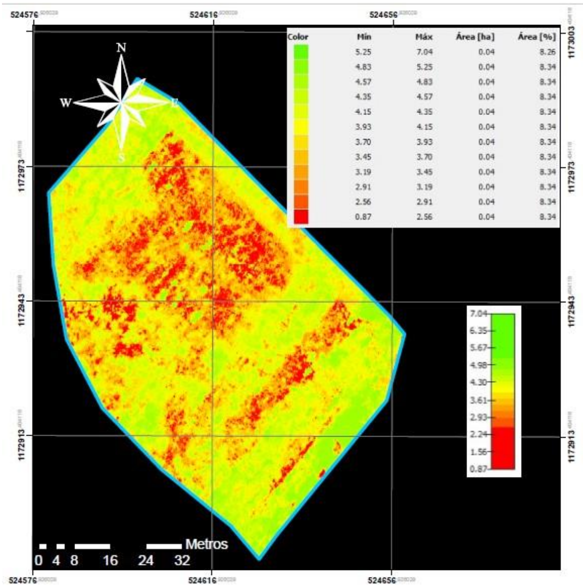

Fig. 6. Multispectral Orthomosaic of the property (second survey). Source: Authors.

TABLE II. CLASSIFICATION OF NDVI INTERVALS OF THE PROPERTY

Category	Area (%) 1st overflight	Area (%) 2nd overflight
Healthy vegetation	8.27	74.98
Mh vegetation	58.37	25.02
Sick vegetation	33.36	0
Zero vegetation cover	0.00	0

Source: Authors

Analyzing the obtained results, it can be observed that in 74.98% of the study area, due to its reflectance, a higher number of vegetal cells are present, indicating an increased presence of chlorophyll in the plant, which is an indicator of a healthy state of the plants with the desired nutrient presence or, in other words, a low presence of nutritional deficiencies in the plant.

Based on the information interpreted in the table, it can also be deduced that 25.02% of the study area is associated with low levels of chlorophyll. Therefore, it was recommended to continue improving their nutritional conditions or provide technical revisions. In other words, priority should be given to monitoring the photosynthetic activity of the plants in these areas to prevent a decrease in chlorophyll levels in the future.

C. Comparison of a Multispectral Survey of the Property

The following information is presented on the phytosanitary status and its percentage area based on the leaf chlorophyll index CI between the multispectral surveys of the property, the evolution of the health status between the first and second image surveys, as well as the average values identified in the coverages that are higher than 0.31, which is associated with healthy vegetation.

According to the index, the vegetal material (Fig. 7) associated with healthy vegetation increased with a variation of 66.71% of the total study area, going from 8.27 in the first flyover to 74.98 in the second. The coverage ranges with some phytosanitary deficiency or stress have decreased by 33.35%, decreasing from 58.37 to 25.02, respectively. Additionally, the vegetation associated with sickness or special requirements of the property has decreased with a variation of 33.36%, reaching zero in the second flyover.

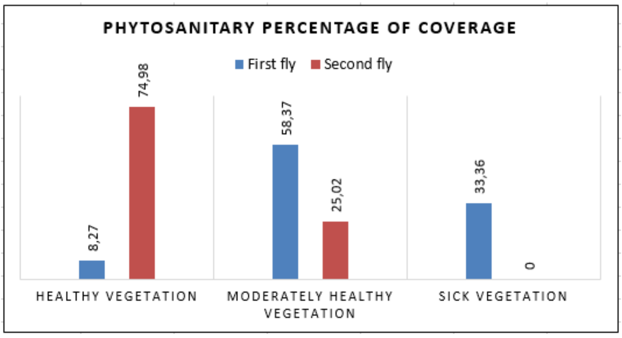

Fig. 7. Percentage comparison of leaf chlorophyll index coverages between multispectral surveys of the property. Source: Authors.

The present variations can be associated with activities inherent to the cultivation processes or to the planting and harvesting strategies implemented in the project, requiring the review of areas with low levels by field personnel.

The average values identified in the multispectral surveys developed that are within the range of healthy vegetation correspond to 41.63%, indicating that the cultivated species maintained a good phytosanitary status.

D. *Third Spectral Survey*

Finally, a third and final multispectral survey was carried out on the property, one month after the second flyover, as shown in Figs. 8 and 9. The process of monitoring and evolution of leaf chlorophyll indices present in the study area was consolidated in the same approach as in the initial flyovers.

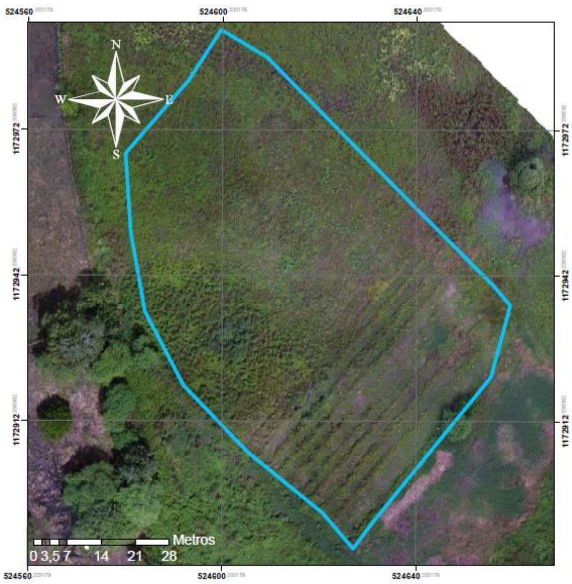

Fig. 8. Orthomosaic of the property during the third overflight. Source: Authors.

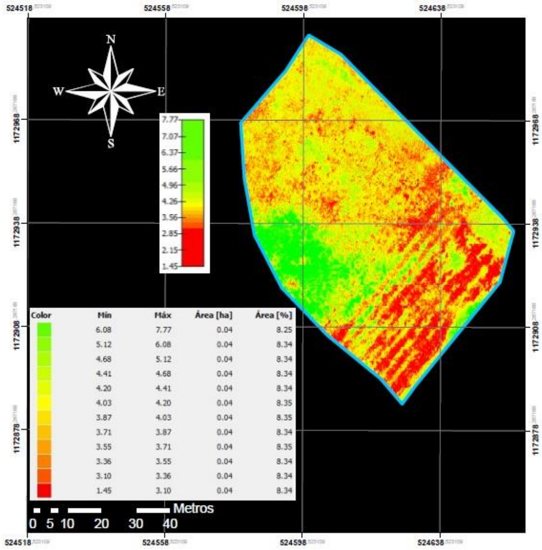

Fig. 9. Orthomosaic of the property's foliar chlorophyll index during the third overflight. Source: Authors.

Upon analyzing the results presented in Table III, it can be concluded that in 91.68% of the study area, due to its reflectance, there is a higher number of plant cells, which indicates an increased presence of chlorophyll in the plants. This is an indicator of a healthy state of the plants, with a desired presence of nutrients, or in other words, a low presence of plant nutritional deficiencies. This is desirable from a chronological perspective since it shows a positive evolution of vegetation indices in the healthy vegetation interval.

TABLE III. CLASSIFICATION OF FOLIAR CHLOROPHYLL INDEX INTERVALS DURING THE THIRD OVERFLIGHT OF THE PROPERTY

Category	Area (%) 2nd overflight	Area (%) 3rd overflight
Healthy vegetation	74.98	91.68
Mh vegetation	25.02	8.32
Sick vegetation	0	0
Zero vegetation cover	0	0

Source: Authors

From the aforementioned information, it can be deduced that the biological material had optimal conditions at that time, derived from the sowing and harvesting process. Similarly, the study area presents an 8.34% that can be associated with low levels of chlorophyll, likely due to the decreased photosynthetic activity of the plants.

E. *Comparison of Multispectral Surveys between the Second and Third Overflights of the Property*

The following information is presented on the phytosanitary status and its percentage area based on the foliar chlorophyll index, between the multispectral surveys of the property, the evolution of the health status between the second and third image surveys, as well as the average values identified in the coverages that are greater than 0.31, which is associated with healthy vegetation.

The vegetal material (Fig. 10) associated with healthy vegetation, according to the index, increased with a variation of 16.70% of the total study area, reaching a value of 91.68. The coverage ranges with some phytosanitary deficiency or stress decreased by 16.68%, from 25.02% to 8.34% in the third flight. This significant decrease is due to the growth in the percentage of healthy vegetation. The vegetation associated with sickness or special requirements on the property has remained with a variation of 0.00%.

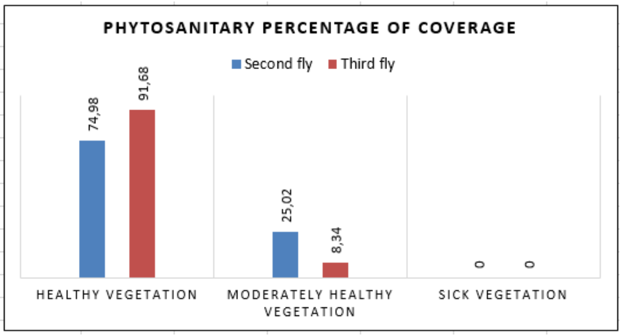

Fig. 10. Percentage comparison of the foliar chlorophyll index between the second and third surveys of the property. Source: Authors.

This suggests that the actions implemented in the project have effectively minimized areas with sick vegetation or with low levels of chlorophyll presence. Instead, almost all areas show high levels of chlorophyll presence in the plants. Therefore, it can be interpreted that the vast majority of the plantation is in excellent health condition with good nutrient levels. Additionally, the average values identified in the multispectral surveys that fall within the aforementioned range correspond to 83.33%, indicating that the species used in the polyculture had a good phytosanitary status.

III. Conclusions

The use of images taken with multispectral cameras and their processing makes it possible to obtain reliable information, which, through spectral analysis, allows for soil characterization and the identification of behavioral patterns in crops. This, in turn, contributes to providing information for the implementation of models in the region that can represent, study, and plan for optimized, efficient, and sustainable production during the phenological cycles of crops.

Thanks to this remote monitoring technology, significant cost savings can be achieved in the investment allocated for agricultural products used for soil fertilization, whether for planting or the growth of plant species. Additionally, it allows for zoning areas with nutrient scarcity and abundance through the analysis of variables such as chlorophyll indices, thereby identifying potential long-term problems early on. This, in turn, can improve the yield per hectare in areas with high agro ecological potential.

Once the three multispectral surveys were carried out in the reference property, a global comparative analysis of the chlorophyll index results was performed with their respective conclusions from the first to the third overflight.

The average values identified in the coverages that fall within the range greater than 3.1 (healthy vegetation), which are associated with a good health status of the plant material due to its high presence of chlorophyll levels in the three overflights, is 58.31%. However, it is worth noting that this range of healthy vegetation increased significantly from 8.27% in the first overflight to 91.8% in the third overflight, showing a considerable growth close to 100% in the presence of healthy vegetation. This allowed us to affirm that its development was adequate and did not present any type of stress that significantly affected the phytosanitary status of the plants or their health with good nutrient levels during the analysis time or during the implementation of the polyculture.

Another noteworthy conclusion is that during the observation time, values of zero were reached in sick vegetation and zero coverage of vegetation, reflecting that, overall, and the selected space for the polyculture model test in the Ponedera municipality property was appropriate, allowing the proper monitoring of the implementation of clean agriculture techniques such as biofertilization and the use of hydroretainers.

In the context of future work stemming from the present research experience, spectral cameras with a higher number of spectral bands, close to 10, to achieve more excellent resolution and the ability to cover most of the relevant electromagnetic spectrum. This will increase precision in chlorophyll index calculations, providing more detailed information for analyzing chlorophyll levels and the presence of nutrients in plants.

Furthermore, it is expected to incorporate artificial intelligence techniques, such as convolutional neural networks, as prediction or estimation strategies. These techniques are anticipated to reveal new perspectives for more efficient and sustainable agricultural management, driving significant resource optimization and decision-making advances.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Luis Gualdron conducted the investigation, raised the problem and carried out the state of the art. Oscar Gualdron generated and implemented the algorithm and carried out the verification tests. Gonzalo Moreno took the database of the images and carried out the documentation and its analysis. All authors participated in the writing of the paper. All authors had approved the final version.

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