EVALUATION OF THE THERMAL BEHAVIOR OF PLANTS IN THE MICROGREENHOUSE WITH MICROBOLOMETRIC IMAGE SENSORS
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EVALUAREA COMPORTARII TERMICE A PLANTELOR IN MICROSERA CU SENZORI DE IMAGINE MICROBOLOMETRICI

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ABSTRACT
In this research, the data from temperature measurements obtained with the InfiRay T2S+ device, an infrared thermal imaging camera have been checked to monitor plant thermal behaviour. Plant leaf temperature is a parameter frequently used as representative for stomatal conductance, as stomatal confinement results in attenuated transpiration, and consequently leads to increased plant temperature. Also, to identify the stress of the plant, indices of thermal and modified stress have been calculated. The results obtained show that the Kalanchoe blossfeldiana species chosen for this study, when exposed to extreme values of temperature or water requirements, presented significant changes in the infrared electromagnetic wave spectra.

REZUMAT
În această cercetare, au fost examinate datele din măsurătorile de temperatură obținute cu dispozitivul InfRay TS2+, o cameră de imagine termică în infraroșu pentru a monitoriza comportamentul termic al plantei. Temperatura frunzelor plantei este un parametru folosit în mod obișnuit ca identificator pentru conductanța stomatelor, deoarece închiderea stomatelor conduce la o transpirație redusă, care, la rândul său, conduce la o creștere a temperaturii plantei. De asemenea, pentru a identifica stresul plantei, au fost calculaţi indicii de stres termic modificat. Rezultatele obținute arată că specia Kalanchoe blossfeldiana aleasă pentru acest studiu, atunci când a fost expusă la valori extreme ale cerințelor de temperatură sau de apă, a prezentat modificări semnificative în spectrele undelor electromagnetice infraroșii.

INTRODUCTION
During the process of growth and development of crops, they are met by situations in which the structures of plants or leaves change, mainly due to the disturbances of environmental factors. Although in the specialized literature can be found described countless methods of research on the evolution of plants under conditions of environmental stress, the method of analysing the behaviour of plants in microgreenhouses with the help of the infrared electromagnetic spectrum (3-14 µm) is not sufficiently known and implemented, perhaps because of the reluctance regarding the costs that are somewhat high. Water stress is an essential abiotic factor that drastically affects plant development (*Cazacu A.C, 2015*). Lack of water, but to the same extent water in excess, presents serious challenges for the survival of crops, because it affects plant growth and reduces productivity. Plants have developed various mechanisms to respond to different environmental stressors (*Shabala S. and Shabala L., 2011*).

The thermal properties of plant leaves are influenced by a complex heterogeneous internal structure that contains a certain amount of water per unit area. This is a solid argument in the decision to conduct research with thermal remote sensing equipment, to which is added the ease of operation, precision and high resolution of infrared thermography (*Ishimwe R., Abutaleb K. and Ahmed F., 2014*). *Buitrago et al (2016)* investigated the stress response in the thermal infrared spectrum of two plant species and found that it had substantial impacts on the long-term thermal spectrum of plants, both in the mid-IR waveband (3–6 µm) as well as in the long wave band (6–16 µm). At the same time, they showed that thermal and water stress led to the change in the emissivity of the two species, but in different directions.

To understand these contrasting remarks, they determined leaf water capacity and the protective layer covering the epidermis thickness as the main factors contributing to the emissivity of the leaves. *Lee A.Y. et al. (2019)* tested a thermographic method capable of accurately measuring the temperature of the leaves of a peach, for measuring the water stress index of the culture. They showed that water stress on the crop, which occurs under water deficit conditions, produces an increase in the temperature of the leaves, which can be established by the proposed thermal imaging technique. The outcomes published by them demonstrate that the infrared images of leaf temperature distribution obtained in a time interval are meaningfully connected to the physiological parameters of culture that are unprotected to water deficiency. The degree or intensity of heat of the plant leaves was exactly extracted from the infrared images to investigate the water content. *Stoll and Jones (2007)*, in their research on mature vines, demonstrated that infrared thermography can be applied as a first step in identifying the onset of plant stress due to changes in stomatal opening. The measurements made can provide precise and sensitive indications of leaf temperature and, consequently, stomatal conductance can be determined. They also suggested that the application of infrared thermography has the potential to contribute to improving the management practices of a wine farm.

Pineda et al. al. (2020) present in their research a comprehensive review of works in which plant and crop thermography is applied to establish water content and discover plant stress. They estimate that in the near future infrared thermography, implemented in high-capacity facilities, will become a tool in plant genetic engineering for the creation of mutant varieties with resistance to pathogens or phenotypes, with much better results established in conditions well determined by abiotic stress. In this way, thermography has a major contribution to the development of the crops of the next generation, of Agriculture 5.0 (*Ragazou K., Garefalakis A., Zafeiriou E. and Passas, I., 2022*).

Ribeiro da Luz and Crowley (2010) state that emissivity is not the product of the reciprocity between solar energy and pigments, even so it represents the efficiency in the release of thermal radiation by the leaf surface. This signify that electromagnetic radiation in the infrared spectrum can include valuable knowledge concerning the leaf biochemistry and the fine structure of simple culture.

The non-invasive thermal inspection method can be used in all processes and for all agricultural products where there is heat transfer. Thermal imaging has grown rapidly and plays a predominant role in many area of agriculture, ranging from nursery observing, supply of water to land, soil pollution stress detection, plant disease diagnosis, yield evaluation, full growth assessment, and fruit and vegetable injury detection (*Ali M.M., Hashim N., Aziz S.A., Lasekan O., 2020*). However, accurate thermal estimation is influenced by the environmental conditions, who influence the thermal properties of the harvest under observation. Therefore, calibrating images according to specific environmental conditions is necessary to compare data from images obtained during different measurement periods and growing seasons (*Ishimwe R., Abutaleb K. and Ahmed F., 2014*).

The main goal of the work is to highlight an approach to the use of thermal images in precision agriculture in general, with a particularity in the assessment of the condition of plants in a micro greenhouse. A second objective is to use the most commonly used long-wave infrared thermal parameters (normalized plant or leaf temperature and crop water stress index) to measure the repercussion of environmental characteristics on the temperature of healthy houseplants.

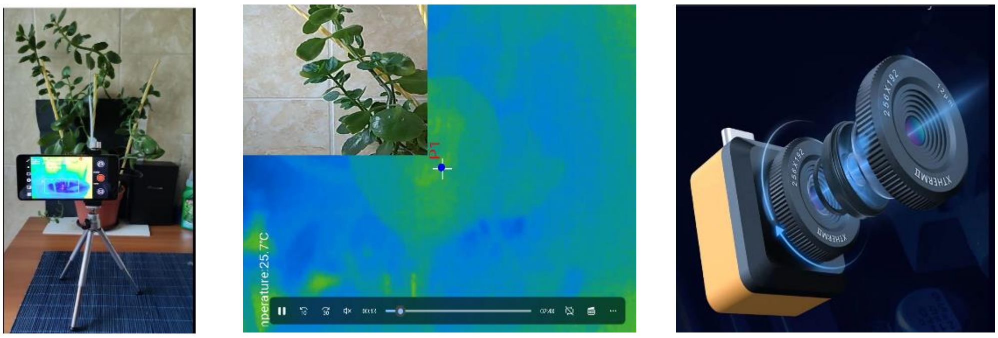
MATERIALS AND METHODS

An uncooled microbolometric technology device incorporate an optical package, a focal plane sensor array and an electronic processing circuit. The microbolometer run by captivating infrared radiation which determine a temperature-induced fluctuate in the resistance of the material. This change in resistance is settled as a variation in voltage while a direct current deviation is applied (*Grimming R., 2020*).

For this study, a species cultivated as an apartment plant (with beautiful flowers that usually appear in spring, but also with glossy leaves that give the plant a pleasant appearance) was chosen, especially due to its ability to manage with excessive conditions such as reduced temperature and drought. Therefore, it is expected that this plant has its own mechanism to survive with environmental stress regime, similar to the structural changes in the leaves, if the stress regime has an extensive duration (*Ştefîrţă A., Leahu I., Toma S., 2015*).

Kalanchoe spp. is a bush-like plant, with heights varying between 30-50 cm. The leaves are green and juicy, and the flowers are small in the form of beautifully coloured stars in red, pink, orange or yellow. Some species are perennial, others are annual or biennial.

Development of the experimental stand. Investigating the thermal radiation characteristics of Kalanchoe blossfeldiana, a small plant suitable for a small space that likes to be watered often, was complicated due to its high thermal reflection (fig.1-left). To make the measuring equipment, materials were chosen to eliminate the reflected and emitted disruptive radiation, the most suitable being those with low reflectance and low emissivity. Another aspect that requires special attention is the minimization of thermal radiation due to the surrounding environment (*Falsetti C., Kapulla R., Paranjape S., Paladino D., 2021*). A black curtain of material was placed at the rear of the pot containing the plant both for better contrast between the plant and its background on the thermal picture, but also to eliminate occasional heat emissions from the surroundings. An additional source of radiation is the thermal chamber that heats up during operation and which must also be avoided (*Wan Q., Brede B., Smigaj M., Kooistra L., 2021*).



a) b)………………… …………c)

Fig. 1 – The experimental measuring stand and InfiRay thermographic camera T2S+

Image capture and analysis. The plant is grown in a simple pot, and the camera was placed on a support that integrates perfectly into any minimalist decor, and directed towards significant areas of interest. The temperature measurement took place under normal laboratory conditions. Thermal images of plant leaves were taken with the thermal camera “InfiraRay T2S+ Thermal Camera for Smartphone” (InfiraRay, P.R. China) which has a sensitivity of ±2°C or ±2% of the measurement range (whichever is greater). In figure 1c, it can be seen the "InfiraRay T2S+" camera. Its technical details are showed in Table 1.

Table 1

Technical specifications of the InfiraRay thermal camera T2S+ (from datasheets)

• Sensor: number of pixels: 49152 elements (256x192), uncooled microbolometer;	• Sensitivity: Average ≤ 60mK@25℃; F0.68;
• Spectral sensitivity: 8μm...14μm;	• Optical date: f=40mm; F #1.0;
• Optical angle: FOV 44.9°×33.4°;	• Measurement range: -20ºC +450ºC (without filter);
• Output: composite video signal (CVBS) (50 fields);	• Control: protocols Cam (USB type C);
• Operating temperature: -20ºC up to 50ºC;	• The frame rate of the image: 25 Hz.
• Dimensions 26×26×24.2mm	• Supported operating system: Android, Harmony OS, iOS

The images and recordings were made with the thermal camera's own software, the Xtherm Android application provided by the manufacturer, which can be downloaded for free from the Google Play store. Using the software, images can be recorded and saved in Live View Stream, and can be simultaneously added up to 3x different temperature measurement fixed points, a temperature spectrum line and a Region of Interest box, also known as ROI boxes, which best characterize the surface temperature (Fig.1b).

Based on the temperature distribution of the foliage, the temperature difference between the leaf and the air and the modified CWSI crop stress index, the thermographic effects of the ambient conditions on the plants can be analysed, such as the thermal state of the plants before or after irrigation. The leaf-air temperature difference ΔT is given by the relation:

$$\Delta T = Tl - Ta \ \ [°C] \qquad (1)$$

where: Tl - the measured temperature of the leaf; Ta – temperature of the surrounding air.

The modified plant stress index, CWSI, was calculated from the relationship proposed by *Jones et al. (2002)* based on captured thermographic images (*Nagy A., 2015*):

$$CWSI = \frac{Tc - Tw}{Td - Tw} \quad (2)$$

where: Td - the maximum reference temperature of the foliage (minimum transpiration); Tw - the minimum reference temperature of the foliage (maximum transpiration); Tc - actual temperature values for each pixel.

Measurement conditions. Light is an important factor for the growth and flowering of Kalanchoe. This plant must not be deprived of light, the lack of light slows down growth and prevents the emergence of new shoots. But the interactive effects of light and soil radiation reflection on leaf temperature can have a negative effect on plant health, causing excessive absolute temperatures. Corresponding images are taken looking perpendicular to the plant structure showing the unshaded and naturally lit parts.

The ambient environment (air temperature and relative humidity, atmospheric pressure, VOC concentration) was continuously monitored with an IoT system consisting of a Bosch BMP680 digital environmental sensor and a Raspberry Pi B3+ development board, the data being saved, visualized and analysed on the Thingspeak IoT cloud platform (https://thingspeak.com/channels/1539770/private_show) made available by the creators of the MATLAB program, Mathworks Inc. - US.

Thermal long-wave infrared (TIR) cameras are calibrated sensors capable of recording emitted radiation in the wavelength range between 8–14 µm and providing images representing the temperature values per pixel (*Leblanc G., Kalacska M., Arroyo- Mora J.P., Lucanus O. and Todd A., 2021*). Thermal imaging allows detailed information about the surface temperature distribution (*Vollmer M. and Möllmann K.P., 2018*). A significant physiological trait for plant growth and development is stomatal activity, having a decisive role in carbon and water balance by permanently checking photosynthesis and transpiration (*Brendel O., 2021*). Consequently, stomatal water conductance is associated with productivity and tolerance to environmental stress and is closely correlated with leaf temperature (*Pineda M., Barón M. and Pérez-Bueno M.L., 2020*).

RESULTS

The thermal sensor generates an image depending on the different amounts of thermal energy it detects. By using a wide palette of different colours to display temperature differences (fig.2), objects and very slight changes in temperature can be detected despite low contrast conditions. In this way, the thermal patterns in an image can be represented using a very large and specific data set. Therefore, this approach allows a complex analysis of a large area of a plant in an image, performing the calculation of the mean temperature or the incidence distribution of temperatures on chosen areas.

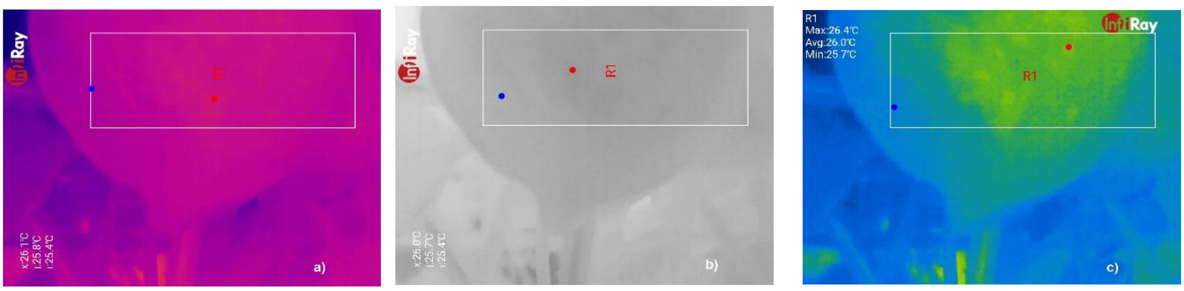


Fig. 2 - The corresponding thermal images (a-c) taken in the afternoon of June 17, 2023

Such image analysis was done with a general-purpose Iron palette (fig. 2a) that quickly identifies thermal anomalies and object heat. In this palette, hot objects are displayed in warm, light colours, while cooler objects are in dark, cool colours. Fig. 2b illustrates the different plant temperature distribution in the Black Hot colour palette. This palette is the inverted version of the White Hot palette, displaying warmer objects in black and cooler objects in white in a clear and realistic image. The Rainbow colour palette (fig. 2c) works well to detect minor temperature differences in a scene despite low contrast conditions. Warm colours illustrate the hottest part of the image and cool colours depict the frosty areas, but add more colours to the mix. It is a very good model for identifying objects in environments with slightest heat dissimilarity.

For the analysis, a region is outlined within the thermal image (rectangles - regions of interest ROI), where the maximum and minimum temperatures are tracked (fig.2).

The ROI box data can also be used as reference data for the temperature histogram. The ROI feature is a perfect tool for analysing different regions of a single thermal image. Each ROI is scalable and movable and can be sized and moved within the live view stream area. In the region of interest selected in figure 2, where the leaf has a low emissivity, it can be seen now that it has a maximum temperature of 26.4 °C, while the average value is just below 26.1°C, almost 0.4 degrees warmer than the environment.

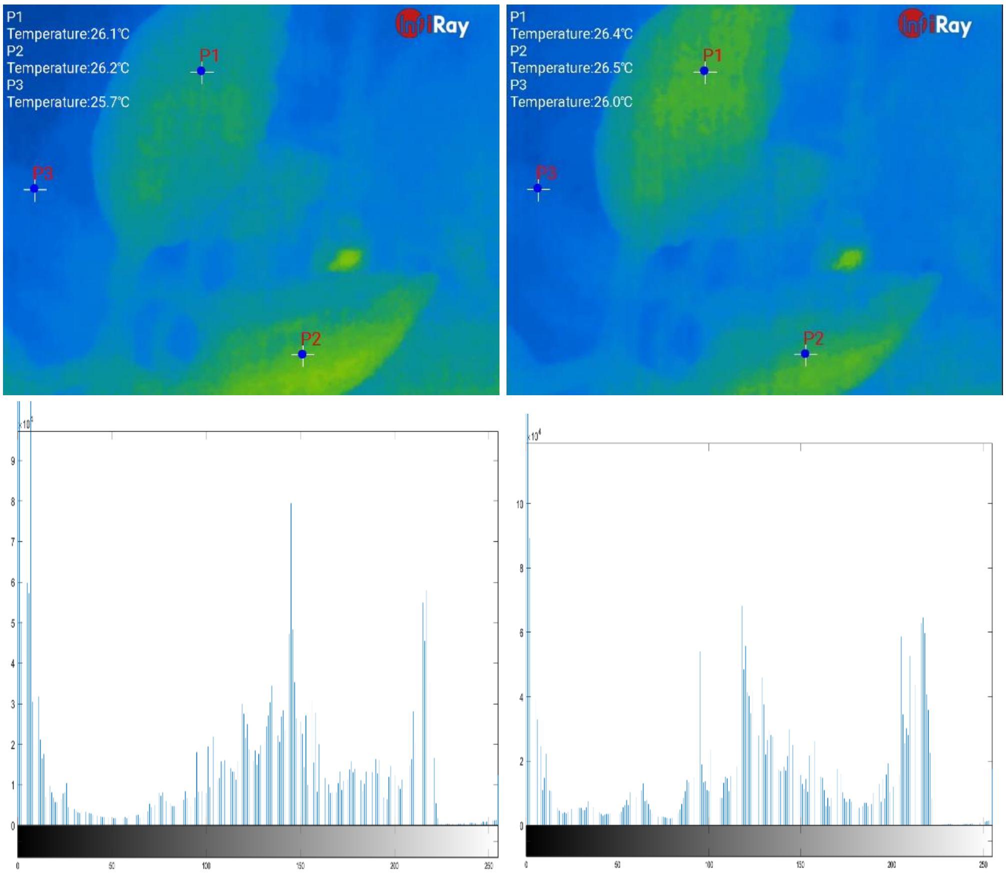


Fig. 3 - The thermal images corresponding to the effects of irrigation on the absolute temperature of the plant

The plant is watered with water at room temperature, differently depending on the periods of growth and rest. From spring to autumn, when the Kalanchoe grows and blooms, it needs a larger amount of water. Watering is done when the soil on the surface is a little dry. The effect of a soil watering operation on the absolute temperature of the plant leaf is shown in figure 3. During the measurements in the afternoon of June 24, a day when the temperature in the external environment reached extreme values of 39°C and the alerts were issued on meteorological conditions of severe weather, no significant change was observed in the absolute temperature of the leaves before and after watering the plant. In Figure 3-right, where the leaf is more heated, the core with high emissivity is at a higher temperature (26.5°C), only 0.5°C higher than the ambient environment, an increase that can be attributed to the acceleration of the process of transpiration of the leaf. The result is in agreement with the one obtained by *Buitrago et. al. (2016)* for beech leaves, who observed that an increase in the moisture content of the leaf increases the emissivity of the leaves.

During the rest period, watering is done with a smaller amount of water, because the Kalanchoe is a plant with juicy leaves and it can withstand the lack of water (for a short period of time). This period of water stress can lead the plant to have: smaller sizes and an earlier flowering (*Petcu E., Terbea M., Lazar C., 2007*).

At the bottom of figure 3 - the two graphs of the histogram of the images made in the Matlab R2022b program are displayed. The input image being an indexed image, the histogram shows the distribution of pixel values depending on the number of colours of the colour map. For the grayscale image, 256 intervals were used by default.

The n intervals of the histogram are each half-open intervals of width $A/(n-1)$. In particular, the p-th interval is the half-open interval.

$$\frac{A(p-1.5)}{n-1} - B \leq x < \frac{A(p-0.5)}{n-1} - B \qquad (3)$$

where: x is the intensity value. The scale factor A and offset B depend on the image class type.

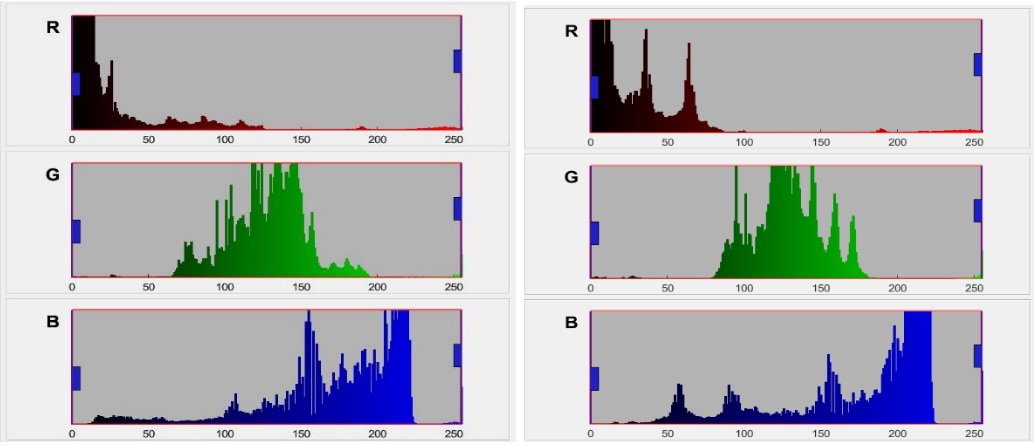


Fig. 4 - Colour histogram of RGB images corresponding to the effects of irrigation on plant temperature

The difference in measured temperature can be visualized much better by calculating the colour histograms of the RGB images (as can be seen in fig. 4). The number of intervals (for each colour component) is entered by the user, being the same for R, G and B colours. The output histogram can be un-normalized or normalized. The temperature increase of the leaves, of approx. 0.4°C, is highlighted by the increase in the frequency of occurrence of the intensity of the colour red - R, simultaneously with the decrease of the frequency of occurrence of the colour blue - B, while the frequency of occurrence of the intensity of the colour green - G remains constant.

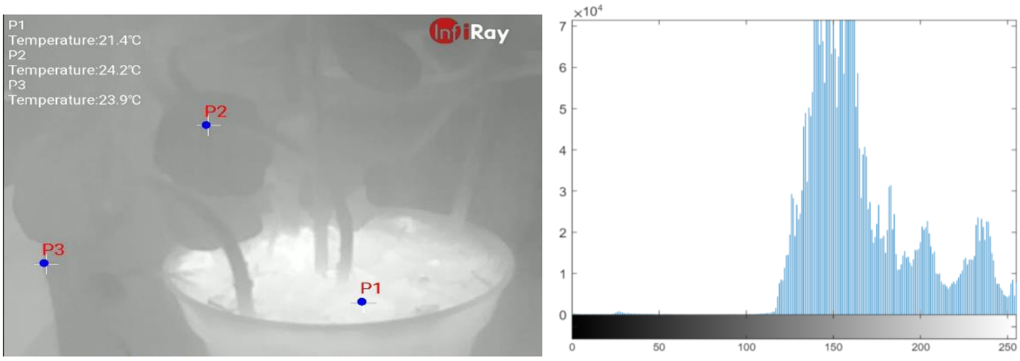


Fig. 5 - Thermographic image of the plant after watering and its histogram from 30.06.2023

In the evening of June 26, the plant was significantly cooler compared to the unstressed vine. No significant temperature difference was found between the leaves and the surrounding air (figure 5). The measurements indicate that the temperature difference ΔT was on average 0.3 °C, lower than that of the plant in the period before watering. Alternatively, it is possible that the irrigation operation affects the structure of the plant and, consequently, increases the reflection of radiation from the ground and thus increases the temperature of the leaves. In the presented thermal image, it can be seen that the soil temperature of 21.4°C is approx.2.8°C lower than the leaf temperature and 2.5°C lower than the air temperature.

The difference between the average leaf temperature and the air temperature was +1.67°C for the period without watering, but it was +0.53 °C for the period following watering. Thus, the effect of irrigation could also be detected on the fruit in addition to the foliage by using thermography. Based on the measurements, the existence of a high risk of water stress was not found. The average values of the modified stress index of the plant were 0.389±0.095 which means that the values were above the threshold value of 0.25. The optimal temperature for the growth and flowering of Kalanchoe varies between 15-25°C. In summer, the plant must be protected from direct sunlight and it is recommended to spray water on the leaves. There is clear evidence in the specialized literature that the plant is very sensitive to low temperatures, it can die if it is kept at temperatures varying between 0-10°C.

Thermal imaging as a non-invasive remote sensing method appears to be a suitable tool for studies where the temperature values of plant foliage, flowers or fruits can be reproduced with greater efficiency and precision than can be achieved with other methods. The choice of the measurement method used depends largely on the architecture of the plants and the availability of exposed flowers or fruits.

One of the main advantages of infrared thermography is that it covers a variety of different positions on the plant structure, which can hardly be achieved using the thermocouple method. In addition, by combining various optical devices and sensors with the performance of a deep learning neural network used for object detection, without applying image enhancement algorithms or excessive processing of measurement data, much-needed information about the condition of plants can be obtained in various weather conditions, such as clear sky, fog and rain, at different intervals.

CONCLUSIONS

The temperature differences observed during the study of the behaviour of the plant subjected to different operations/situations are encouraging for the application of the thermal image as a useful tool to make a correct assessment in the event of water stress states or to take advantage of the application of this methodology in the management of plant growth, or even more precisely, in the realization of irrigation control applications, which ensure an optimal water regime.

The productivity and quality of plant development are strongly influenced by the limiting abiotic conditions (thermal and water stress) manifested during the experimental period. Reducing the drastic effects of water stress can also be achieved by accumulating osmoprotectors, maintaining turgor, leading to a decrease in the rate of transpiration and the closing of stomata.

The processed thermal image can be displayed in a certain colour spectrum by using colour palettes. The cost vindication for implementing the thermography method increases as the prices of electronic elements decrease. Nowadays, infrared thermal devices provide up to 16 times the quality of image of devices used in decade past, for nearly the same cost.

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