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USING INFRARED THERMOGRAPHY FOR DETAILED MONITORING OF CABBAGE WATER AND HEAT STRESS

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Abstract

The research was conducted on the farm of the agricultural research station, Agricultural Research Center, Tripoli, Libya (latitude of 32° 12` 25`` and longitude of 13° 62` 16``) during the season of 2021-2022. Cabbage and lettuce crops were planted at greenhouse condition in November 2021. The objective of this study was using alternate representations of infrared thermography IR to detect the vegetative indicators addition to continuously monitor cabbage and lettuce plants growing conditions for discrimination plants stresses under the shortage of nitrogen and irrigation water, using four levels of nitrogen fertilization (0, 50, 100 and 150% of Nitrogen recommended). Also four levels of water regime (50%, 75%, 100% and 125% of ETc) . The leaf-to-air temperature difference (ΔT), The relationship between the temperature of the canopy (Tc) and temperature of soil (Ts), pair is best suited to find the plant under water stress. Water stress index (CWSI) and stomatal conductance index (Ig) using various reference and non-reference thresholding techniques were tested. In this research a thermal imaging system was used to measure the leaf-temperature changes of several crops according to plant stresses. Results showed by applying 100% fertilization and 100% ETc to cabbage. The heat stress was the highest as MTD, maximum temperature difference, normalized relative canopy temperature were 8 and 0.32 C when the water stress as CWSI, IG index of stomatal conductance were 0.5 and 4.15 for cabbage in100% ETC and 150%F. Finally, possibility of using infrared thermography for detailed and continuous monitoring showed its ability to distinguish and show the thermal and water stress of plants under nitrogen and water deficiency.

Key words: *cabbage, infrared, thermography, monitoring, heat, water, stress*

INTRODUCTION

The United Nations estimated that by 2050 the world population is expected to reach 9.8 billion people. This leads to an increase in the demand for food, and the agricultural sector faces many obstacles, such as risky temperatures, soil degradation and expected drought. So agricultural practices are needed to ensure that high yields in 2020, world production of cabbages were 71 million tons, led by China with 48% of the world total [8].
The most productive agricultural lands in Libya are limited to a strip along the Mediterranean Sea, where most of the rain falls. Agriculture contributed about 2% to the gross domestic product of Libya in FAO 2011 These challenges can be addressed by integrating Libyan soil resources it will lead Using of the greenhouse is one of the fast solutions to meet the demand for vegetables in light of climate changes and the lack of arable land in Libya. The ideal conditions Plants need air, light, warmth, water and nutrients to be healthy. If a plant doesn't have one of these requirements it could affect its growth **[7].**
Climate change presents a major challenge for developing countries that lack adequate resources. Climate change will lead to severe weather events for Libya, affecting both the intensity and frequency of extreme temperature, precipitation, rainfall, and drought. The global mean temperature has increased gradually by 0.74 ± 0.18 ˚C during the 100 years from 1906 to 2005, and can be expected to reach an increase up to 1.5 to 2.0 ˚C by the year 2100 [6].
The Cruciferous vegetables included cabbage are considered to be excellent source of some bioactive phytochemicals such as

glucosenolates, folate, myricetin, selenium, vitamins (A, B1, B2, B6, C, and E), minerals (Mn, Ca, K and Mg) and protein. All of these compounds are important in human diet in order to protect against cancer of prostate, lung and breast [15].

The quantity of water needed by plants and the timing of irrigation are managed by predominant climatic conditions, crop type and its growth stage, holding capacity of soil moisture and the intensity of root system as determined by crop variety, growth stage and soil type. Water deficit stress is considered one of the most critical abiotic stresses for cabbage productivity. Cabbage has been categorized as moderately susceptible to irrigation water deficit stress and it is more sensitive especially in the period of head formation, therefore insufficient available water limits the yield and quality of cabbage [14].

The plant stress is one of the most significant factors affecting plant fitness and, consequently, food production. However, plant stress may also be profitable since it behaves hormetically; at low doses, it stimulates positive traits in crops, such as the synthesis of specialized metabolites and additional stress tolerance. The controlled exposure of crops to low doses of stressors is therefore called hormesis management, and it is a promising method to increase crop productivity and quality. Nevertheless, hormesis management has severe limitations derived from the complexity of plant physiological responses to stress [19].

Plant monitoring data help characterize ecosystem responses to weather and climate, land plant changes, and abiotic stresses. the farmers and breeders aim to improve crop responses to abiotic stresses and secure yield under adverse environmental conditions [3]. To achieve this goal and select the most resilient genotypes, plant breeders and researchers rely on phenotyping to quantify crop responses to abiotic stress. Recent advances in imaging technologies allow researchers to collect physiological data non-destructively and throughout time, making it possible to dissect complex plant responses into quantifiable traits. The use of image-based technologies enables the quantification of crop responses to stress in both controlled environmental conditions and field trials [16].

Abiotic stresses such as temperature, insolation, drought, flooding, salinity, agricultural practices, and the use of machinery and other agricultural equipment. These are both physical and chemical factors. subtle changes in canopy temperature, which is a function of the temperatures of the leaves of a plant canopy, can be measured with a thermal imaging camera, also known as an infrared camera or infrared thermography, which forms a temperature image using emitted long wave radiation. For decades, satellite-based thermal imaging cameras have been extensively used to monitor vegetation and crop conditions on a regional scale, estimate energy fluxes and soil moisture, detect plant water stress, predict yield, and monitor regional drought. However, their usefulness in precision agriculture and small area phenotyping has been mixed due to the fact that their spatial resolution and the homogeneity of data with large pixels is typically not suitable for precision agriculture. cabbage is one of the vegetables that are most susceptible to heat, water and nitrogen stress.

Reducing stress on plants is one of the major tasks in maintaining crop quality and profitability [4].

These studies proposed that drip irrigation and fertilization can achieve higher water and fertilizer use efficiency and recommended improved water and fertilization management schemes for these crops compared with standard practices. But may also cause soil environmental deterioration. To improve the efficiency of water and fertilizer use and determine the appropriate amount of water and fertilizer for crop growth, some authors have studied winter wheat, potato, tomato, broccoli, onion and areca nut, among other crop species. Doing this sustainably is an even bigger challenge. So the continuous monitoring of plants stresses to make data informed assessments and more accurately provide direct support to their plants. Decoding the Language of Plants and

Vegetables to understanding our plants and vegetables is that it is easier to control crop yield quantities throughout the growing season [23].

Plant growth monitoring is an important aspect of precision agriculture implementation. The monitoring can be performed by estimating the volume by the result of Three-dimensional reconstruction by using Close-range Photogrammetry. For the validation purposes and its functionality for modelling and estimating volumetric objects, Chinese cabbage with four size variations at different ages was used (14, 21, 28, and 35 Days After Transplant). As the result, the developed system could observe and generate the plant in a three-dimensional manner resemble the actual plant model. Further improvements in accuracy need to be made for precise measurements as well as validation for other crop types. There are several options to monitor vegetables, one of them is by Infrared thermography is the process of using a thermal imager to detect radiation from an object. Infrared thermography is the process of using a thermal imager to detect radiation (heat) coming from an object, converting it to temperature and displaying an image of the temperature distribution [17].

Infrared thermal imaging is a non-destructive testing technology that can be used to determine the superficial temperature of objects. This technology has an increasing use in detecting diseases and distress in animal husbandry within the poultry, pig and dairy production. The process can identify changes in peripheral blood flow from the resulting changes in heat loss and; therefore, have been a useful tool for evaluating the presence of disease, edema, and stress in animals. also detect plants heat stress [20].

Optical sensors have been used to study (a) the response of plants to pathogens, pests and abiotic stressors; (b) to identify primary disease foci; (c) to monitor resistance or susceptibility of different plant genotypes to specific stress factors; (d) to evaluate the severity of symptoms; (e) and to assess plant biomass and yield. Stomatal activity is one of the most important physiological traits for plant growth and development. It plays a crucial role in the carbon and water balance by controlling photosynthesis and transpiration. Hence, stomatal conductance to water (gs) is related to yield and to the tolerance of environmental stresses and correlates strongly with leaf temperature [12].

Studied water and nitrogen productivity for cabbage under the shortage of nitrogen and irrigation water during growing cabbage (Saturn) plants. Mass production, nitrogen productivity, water productivity, chlorophyll A, chlorophyll B and total chlorophyll, respectively were test under using four levels of nitrogen fertilization (0, 50, 100 and 150% of Nitrogen recommended) and also four levels of water regime (50%, 75%, 100% and 125% of ETc) in Libya conditions. The optimum conditions in drip irrigation greenhouse for crops grow were provided to give us high yield, quality production for cabbage crops. Applying 100% N fertilization and 125% ETc to cabbage was the highest nitrogen productivity of 1,132.3 kg yield /kg N, water productivity 17.32 kg/m^3 and mass production of 17.57 Mg/ha. The highest value of chlorophyll A, chlorophyll B and total chlorophyll obtained with 100%N and 100% ETc applied water for cabbage were (0.505, 0.753 and 1.258 mg/100gm), respectively [11].

Radiation is a form of heat loss through infrared rays involving the transfer of heat from one object to another without physical contact. Skin emissivity is an important factor in determining the true skin temperature, and through the assessment of surface temperature, it is possible to acquired knowledge regarding physical and healthy status of humans and other living creatures [2].

Because numerous aspects might influence thermal imaging, it is vital to evaluate the likely impact of the measurement environment on the information to be collected from the picture when operating at a certain observation scale. Thermal imaging cameras, like conventional imaging cameras, are built with a lens that focuses infrared light onto a detector. The radiation that strikes a thermal camera originates from three sources. The camera picks up radiation Wobj from the target item as well as radiation Wamb from its surroundings, which has been reflected onto the object's surface [5].

Thermal long-wave infrared (TIR) cameras (or simply thermal cameras) are calibrated sensors able to record emitted radiation in the thermal images representing temperature values per pixel. Thus, conventional, timeconsuming ground-based measurements can be feasibly replaced by thermal images evaluating plant physiological status at different scales in short periods of time. Additionally, highly sensitive thermal cameras with a relatively simple operational procedure have become more available to research groups, at a lower cost and at higher spatial resolution [13].

In this study the main objectives of this research were the possibility of using infrared thermography for detailed and continuous monitoring of plant. Display the temperature difference, crop water stress and stomatal conductance index changes under greenhouse condition

MATERIALS AND METHODS

The study was conducted at agriculture greenhouse, Agricultural Research center, Tripoli, Libya (latitude of 32° 12` 25`` and longitude of 13° 62` 16``) during the winter season of 2021-2022. Cabbage plants were planted in November 2021. Different agricultural practices were performed as recommended. Plants monitoring data collecting to express about heat, water, and nitrogen stresses. Using a new technique application of digital and thermal imaging to detect plants heat stress

Cabbage and greenhouse, soil, and water, Phosphoric, Nitrogen fertilizer, Thermal camera with testo 865 and IR soft program, as a materials were used under this study.

Cabbage

The Cabbage seed was obtained from private company, Tripoli Governorate, Libya. Cabbage and lettuce nurseries were made for healthy seed growth. Coming from Jebal Atias Co. Street NO. 9, Ghout Alshaal, Tripoli, Lybia. Orgin USA standard seed from SAKATA with 94% Germination product date 9/2020 Cabbage, cultivars of *(Brassica Oleracea*), is a leafy green, as showed in Photo 1.

Photo 1. *Brassica Oleracea Capitate* – Cabbage .
Source: Original photo taken by authors.

Agricultural greenhouse

Plastic film greenhouse were used dimensions were 60 × 30 = 1,800 m^2 The materials covered by flexible plastic films, polyethylene and polyester material. Steel framing as vertical support structure. which supports the weight of the roof? There are number of structural parts of a greenhouse roof which include bar caps, gutters, purlins, trusses, ridge cap, sash bar, and side posts as shown in Figure 1.

Fig. 1. Isometric of greenhouse frame
Source: drawing by authors.

Soil physical and chemical properties

The physical and chemical analysis of soil for this experiment were tested at Tripoli Center for Agricultural Research laboratories. Soil mechanical analysis was sandy loam

The drip irrigation system

An irrigation system has been installed under a drip system consisting of main and laterals line (24 lines) the length of each line was (21 meters) with a diameter of (12 mm) and GR long path flow emitter type building In-line discharge (4 liters/hour) at a pressure of (0.5 bar) and was connected to each line with a stopcock to control the amount of irrigation water and connected with a branch line of diameter (32 mm) and the water source (a water tank with a capacity of 8 m^3 and a suction pump of 1.5 bar).

Nitrogen, Phosphorous and potassium

Phosphorous and potassium fertilizers were applied in liquid form during irrigation. Phosphate and potassium fertilizer were added in the form of Phosphoric Acid H_3PO_4 85%(3.600L) and JOSPA K50. Nitrogen fertilizer was added in the form of nitrate (3.88 kg) and applied in four equal doses: The first one at 20 days after transplanting on 29/11/2021 and the other on 29/12/2021 and the other on 9/1/2022, while the last dose from potassium only on 4/2/2022.

The thermal monitoring system

Infrared thermography and thermal camera with testo 865 and IR soft program to monitor the level of stress in plants by the thermal imager testo 865s. MATLAP software package was used to analysed the digital images. Figure 2 showing in Thermal monitoring system.

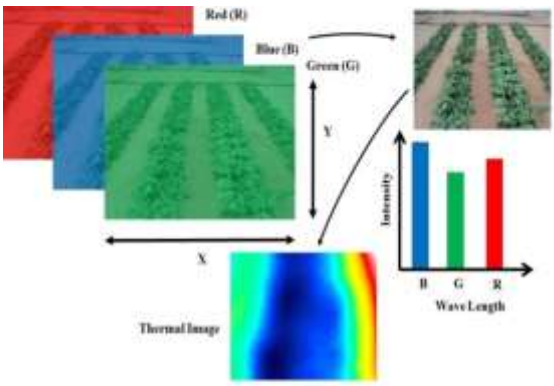


Fig. 2. The digital and thermal monitoring system component
Source: drawing by authors.

The Thermal camera

The thermal imager testo 865s is the ideal entry into the world of thermography. It impresses with the best image quality in its class and intuitive operation in a modern tile look. The testo 865s fits comfortably in the hand and is robust enough to withstand the rigours of everyday use. Helpful functions such as IFOV-Warner and Scale Assist ensure even better thermal images. All that combined with an unbeatable price-performance ratio. Switch on point, know more.

Image quality with IR resolution of 160 x 120 pixels (with testo Super Resolution technology 320 × 240 pixels). Thermal sensitivity of 0.1 °C., automatic detection of hot and cold spots, free analytical software for creating professional reports. fast measurement with fixed focus and measuring accuracy of ±2 °C Photo 2 and Table 1, which shows and explain the Thermal imaging camera and Technical Data of Thermal imaging camera- testo 865s.

Photo 2. Thermal imaging camera- testo 865s
Source: Original photo taken by authors.

Table 1. Technical Data of Thermal imaging camera- testo 865s

Infrared image output		Image presentation	
Infrared resolution	160 x 120 pixels	Display type	8.9 cm (3.5") TFT, QVGA (320 x 240 pixels)
Thermal sensitivity	<0.1 °C (100 mK)	Display option	IR image only
Field of view	31° x 23°	Colors	4 (iron, rainbow, cold-hot, grey)
Minimum focus distance	<0.5 m	Measurement	
Geometric resolution (IFOV)	3.4 mrad	Measuring range	-20 to +280 °C
Super Resolution (Pixel)	320 x 240 pixels	Accuracy	±2 °C, ±2 % of mv

Source: Camera- testo 865s Catalogue.

IRSoft · PC-Software

The IRSoft software is used for the analysis, processing and archiving of the images recorded by a testo thermal imager. It also has integrated reporting for the clear presentation of the data. The settings can be performed on the connected thermal imager via the instrument control.

System requirements: Operating system, the software run on the following operating systems: Windows 8 (32 bit / 64 bit) Windows 10 (32 bit / 64 bit). Computer The computer have the requirements of the corresponding operating system. Interface USB 2.0 or higher. Internet Explorer 6.0. Intel Core i3-2310M 2.1 GHz, Intel Pentium Dual Core E2220 2.4 GHz 2.4 GHz 4 GB RAM. 500 GB available hard drive capacity. DirectX 9c graphics device.

User interface: Interface have three items ribbon, work space and status bar to detect thermal image (Photo 3).

Photo 3 present IRSoft software interface.

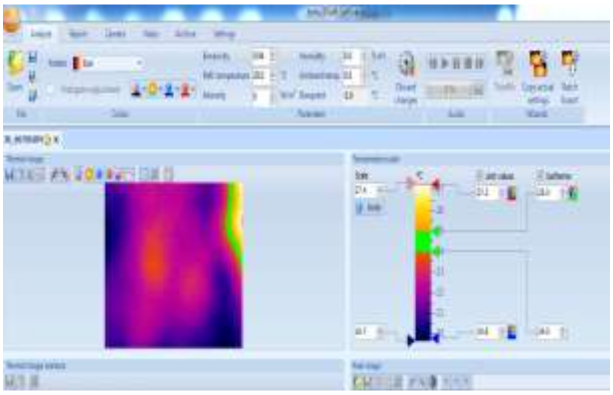
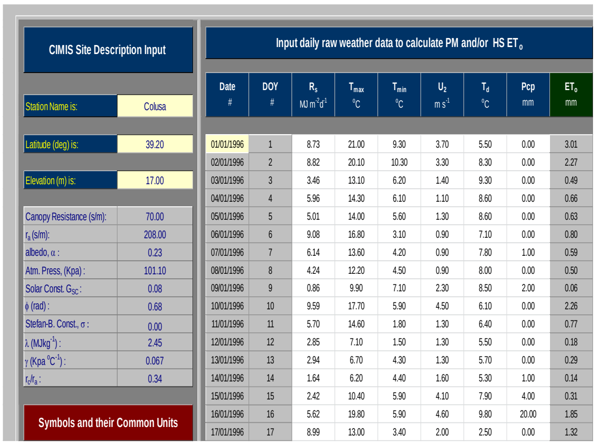


Photo 3. IR soft interface, ribbon, work space and status bar
Source: Authors' determination.

CUP plus model

CUP plus model application of Cabbage and lettuce under Libyan conditions. This worksheet, CUP plus program, has been developed and created by California Department of Water Resources and Department Land, Air and Water Resources, University of California, USA [21]. To estimate the reference evapotranspiration (ETo) CUP plus model application Interface of monthly climate input worksheet is showed in Photo 4.



CIMIS Site Description Input	
Station Name is:	Colusa
Latitude (deg) is:	39.20
Elevation (m) is:	17.00
Canopy Resistance (s/m):	70.00
r_a (s/m):	208.00
albedo, α :	0.23
Atm. Press, (Kpa) :	101.10
Solar Const. G_{SC} :	0.08
ϕ (rad) :	0.68
Stefan-B. Const., σ :	0.00
λ ($MJkg^{-1}$) :	2.45
γ (Kpa $^{o}C^{-1}$) :	0.067
r_c/r_a :	0.34
Symbols and their Common Units	

Input daily raw weather data to calculate PM and/or HS ET_o

Date #	DOY #	R_s $MJ\,m^{-2}d^{-1}$	T_{max} ^oC	T_{min} ^oC	U_2 $m\,s^{-1}$	T_d ^oC	Pcp mm	ET_o mm
01/01/1996	1	8.73	21.00	9.30	3.70	5.50	0.00	3.01
02/01/1996	2	8.82	20.10	10.30	3.30	8.30	0.00	2.27
03/01/1996	3	3.46	13.10	6.20	1.40	9.30	0.00	0.49
04/01/1996	4	5.96	14.30	6.10	1.10	8.60	0.00	0.66
05/01/1996	5	5.01	14.00	5.60	1.30	8.60	0.00	0.63
06/01/1996	6	9.08	16.80	3.10	0.90	7.10	0.00	0.80
07/01/1996	7	6.14	13.60	4.20	0.90	7.80	1.00	0.59
08/01/1996	8	4.24	12.20	4.50	0.90	8.00	0.00	0.50
09/01/1996	9	0.86	9.90	7.10	2.30	8.50	2.00	0.06
10/01/1996	10	9.59	17.70	5.90	4.50	6.10	0.00	2.26
11/01/1996	11	5.70	14.60	1.80	1.30	6.40	0.00	0.77
12/01/1996	12	2.85	7.10	1.50	1.30	5.50	0.00	0.18
13/01/1996	13	2.94	6.70	4.30	1.30	5.70	0.00	0.29
14/01/1996	14	1.64	6.20	4.40	1.60	5.30	1.00	0.14
15/01/1996	15	2.42	10.40	5.90	4.10	7.90	4.00	0.31
16/01/1996	16	5.62	19.80	5.90	4.60	9.80	20.00	1.85
17/01/1996	17	8.99	13.00	3.40	2.00	2.50	0.00	1.32

Photo 4. CUP plus model application Interface of monthly climate input worksheet
Source: Authors' determination.

Experimental design

The experimental design was set up as a spilt, spilt plot design with three replicates. The treatments were applied under the shortage of nitrogen and irrigation water, using four levels of nitrogen fertilization (0, 50, 100 and 150% of Nitrogen recommended) and four levels of water regime (50%, 75%, 100% and 125% of ETc) (Figure 3).

The leaf-to-air temperature difference (ΔT), The relationship between the temperature of the canopy (Tc) and temperature of soil (Ts), pair is best suited to find the plant under plant stresses. Also determining reference evapotranspiration (ETo), crop coefficient (Kc) values, crop evapotranspiration (ETc), and evapotranspiration of applied water (ETaw), water stress index (CWSI) and stomatal conductance index (Ig) using various reference and non-reference thresholding techniques were estimations.

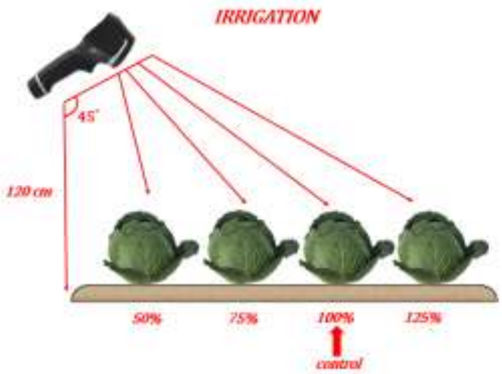


Fig. 3. Photographing transactions with thermal images for Cabbage
Source: Own results.

Irrigation water requirements

Irrigation water requirements for the drip irrigation system was calculated based on the meteorological data collected from Tripoli weather station which is next to the experiment. Irrigation water requirements were based on the calculation of potential evapotranspiration using CUP plus model application.

Reference Crop Evapotranspiration

Because of the extra high aerodynamic resistance induced by low wind velocity (0.01–0.3 m s^{-1}), ETo will be underestimated in greenhouse under low wind velocity situations [9]. Therefore, the ETo inside greenhouse, referred to $ETo_{,GH}$, was computed using a modified Penman–Monteith method established in greenhouse [10], in which a constant aerodynamic resistance of 295 s m^{-1} was utilized to counterbalance the effect of the low wind speed on ETo.

$$\mathbf{ETO}_{GH} = \frac{0.408\Delta(R-G)+Y(\frac{628}{(T+273)})VPD}{\Delta+1.24Y} \text{..........(1)}$$

where:

$ETo_{,GH}$ is the reference evapotranspiration (mm d^{-1}); Rn is the net radiation (MJ m^{-2} d^{-1}); G is the soil heat flux density (MJ m^{-2} d^{-1}); T is the mean air temperature (∘C);Δ is the saturation slope of the saturation vapor pressure curve at T (kPa $∘C^{-1}$); γ is the psychometric constant (kPa $∘C^{-1}$); and VPD is the vapor pressure deficit (kPa).

Cabbage Crop Coefficient

The Cabbage and lettuce crop coefficient (K_{cb}) was defined as the ratio of crop transpiration (T_r) to reference crop evapotranspiration ETo when the average soil water content of the root zone was adequate to sustain full plant transpiration [1].

At the daily base, the crop transpiration amount can be regarded as the daily sap flow when the water storage in plant tissue is negligible. Then, K_{cb} is calculated as the ratio of plant sap flow (SF) to $ETo_{,GH:}$

$$\mathbf{K_{cb} = SF/ETo}_{,GH} \quad \text{.....................(2)}$$

where:

K_{cb} is the Cabbage and lettuce crop coefficient; SF is the daily sap flow amount (mm d^{-1}); and $ETo_{,GH}$ is the daily reference evapotranspiration (mm d^{-1}) in greenhouse.

Crop Water Stress Index (CWSI)

The measurement of canopy temperature as an indicator of stress was put on a sound footing by [18] who defined a 'Crop Water Stress Index' (CWSI). The index IG was proportional to the leaf conductance to water vapor transfer which was calculated from leaf temperatures according to the formula 3.

$$\mathbf{IG = (T_{dry}-T_{leaf})/ (T_{leaf}-T_{wet})} \text{..........(3)}$$

This index is theoretically proportional to stomatal conductance (gs). An index analogous to [18] crop water stress index (CWSI) was also calculated, using Formula 4.

$$\mathbf{CWSI= (T_{dry}-T_{leaf})/ (T_{dry}-T_{wet})} \text{..........(4)}$$

Heat Indices Basics IR

To consistently compare plant temperature across the plant age, we calculated the deviation of Tp from ambient temperature (dTp=Tp - Ta), a measure often used in field phenotyping studies of heat tolerance.

Canopy Temperature CT

[22] affirmed that Canopy temperature measured with the infra-red can be utilized successfully to indicate water stress in grapevines by comparing them to well-irrigated reference vines.

ΔT normalized canopy or leaf temperature

$= T_{canopy}-T_{air}$ or $T_{leaf} - T_{air}$..........................(5)

MTD, maximum temperature difference = $T_{leaf\_max}-T_{leaf-min}$..(6)

NRCT, normalized relative canopy temperature =

$$\frac{(T\ leaf-Tminimum)}{(Tmaximum-Tminimum)} \text{.................................(7)}$$

Index (CWSI) program mode for plant greenhouses.

RESULTS AND DISCUSSIONS

The results were revealed by using a new technique application of digital and thermal imaging for showing plants monitoring data collecting to express about heat, water, nitrogen and heavy metal stresses during Cabbage plants growth periods.

Detects Heat Stress by thermal images for Cabbage Crops

The temperature of air, soil, canopy, and leaf were measured by IR image affected by different irrigation and fertilization levels of Cabbage crop at different fertilization levels. The interaction between the water regime and nitrogen fertilization levels has an effect on Cabbage temperature indices. The results were discussed during irrigation levels 50% ETC, 75% ETC, 100% ETC and 125% ETC. Also, they are shown in Photos 5 and 6 at different levels of nitrogen fertilization: 0, 50, 100 and 150% at average temperature for growth periods.

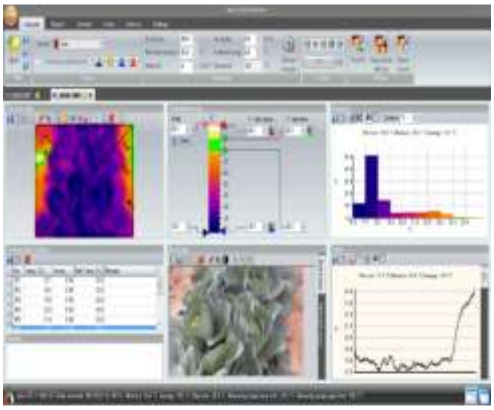


Photo 5. IR soft interface, ribbon, work space and status bar for Cabbage Crop.
Source: Own results.

With the control level of fertilization (0%), Fig. 4 showed the maximum value of Cabbage temperature of air, soil, canopy, and leaf were 31, 26.5, 32, and 21 °C, recorded with 100 % ETC. also showed the minimum value were 28, 26, 22 and 20 °C. at 50% ETC.

With the control level of irrigation (100% ETC), Fig. 5 showed the maximum value of Cabbage temperature of air, soil, canopy, and leaf were 24.5, 23, 20.5, and 18 °C, recorded with 100 % nitrogen fertilization also showed the minimum value were 25, 24.5, 20.5 and 19.5 °C recorded with 0 % nitrogen fertilization level.

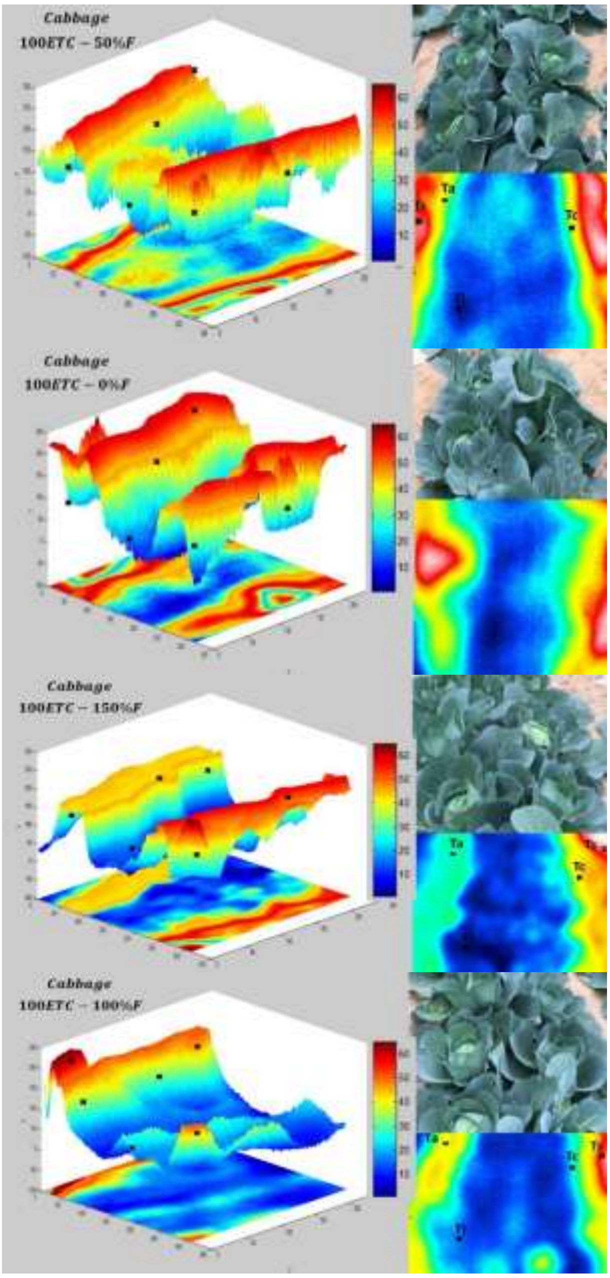


Photo 6. Cabbage temperature recorded under different fertilization at 100% ETC irrigation levels.
Source: Own results.

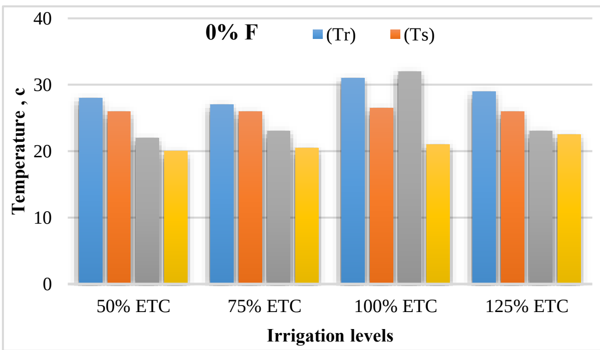


Fig. 4. Relationship between heat stress indices and irrigation levels of cabbage crop
Source: Own results.

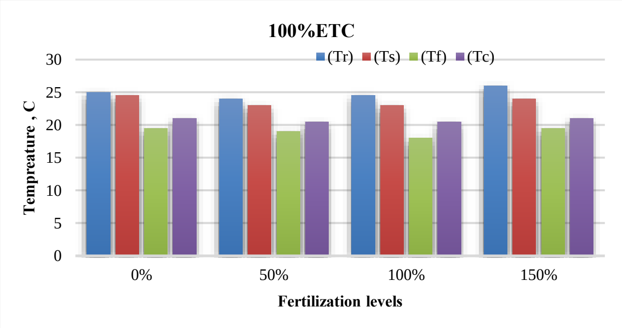


Fig. 5. Relationship between heat stress indices and fertilization levels of cabbage crop
Source: Own results.

With the levels of irrigation the maximum value of cabbage temperature of maximum temperature differences and normalized relative canopy temperature were 7.23 and 0.87 °C, also showed the minimum value for the same indices were 2.58 and 0.78 °C. Also, in Figures 6 and 7, where the levels of fertilization showed the maximum value of maximum temperature difference, and normalized relative canopy temperature were 6.63. and 0.84 °C, also showed the minimum value for the same indices were 2.29 and 0.45 °C.

Linear regression analysis was performed to predict the MTD and NRCT at different irrigation and fertilization levels. The following equation represents the relationship.

MTD:

$y = 1.5621x + 1.0424$ $R^2 = 0.9988$

$y = 1.463x + 1.1475$ $R^2 = 0.9575$

NRCT:

$y = 0.0311x + 0.749$ $R^2 = 0.9978$

$y = 0.1253x + 0.3291$ $R^2 = 0.9904$

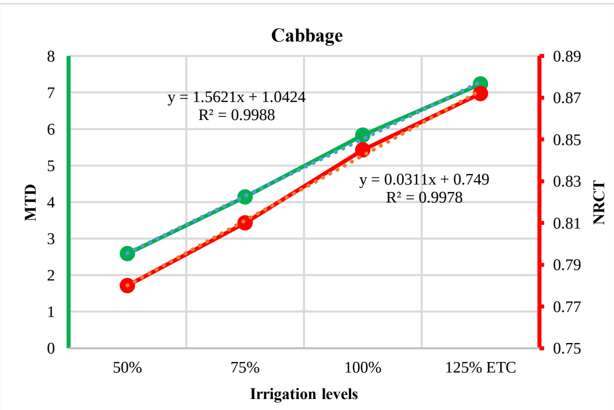


Fig. 6. Maximum temperature difference and normalized relative canopy temperature with irrigation levels of cabbage crop
Source: Own results.

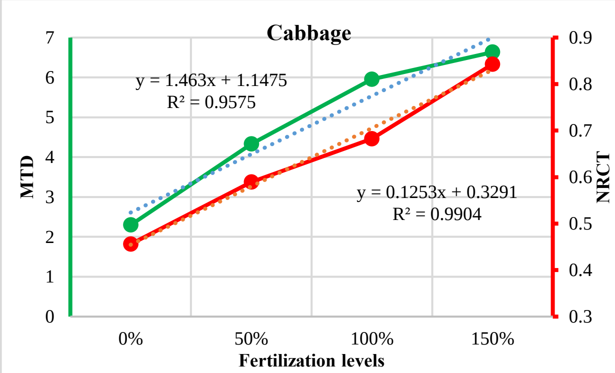


Fig. 7. Maximum temperature difference and normalized relative canopy temperature with fertilization levels of cabbage crop
Source: Own results.

Cabbage Plant Water Stress With Water Regime Levels

As it is presented in Figure 8, with the levels of irrigation showed the maximum value of that the crop water stress index, and the index of stomatal conductance were 0.62. and 2.77, also showed the minimum value for the same indices were 0.36 and 1.8.

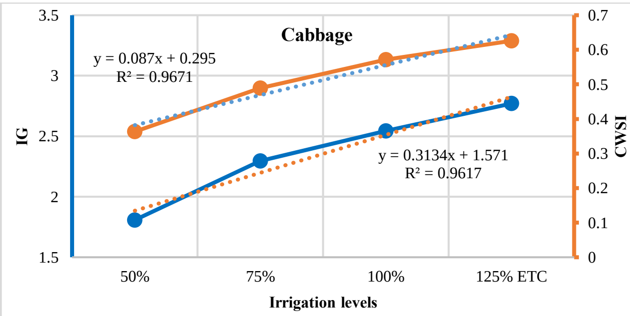


Fig. 8. Crop water stress index, and the index of stomatal conductance with irrigation levels of cabbage crop
Source: Own results.

Linear regression analysis was performed to predict the CWSI and IG at different irrigation levels.

The following equations represent the relationship.

CWSI:

$y = 0.087x + 0.295$ $R^2 = 0.9671$

IG:

$y = 0.3134x + 1.571$ $R^2 = 0.9617$

Detecting Water Stress Indices with Fertilization Levels For Cabbage Crop

Cabbage vegetative measurements such as crop water stress index and index of stomatal conductance were affected by four levels of nitrogen fertilization (0, 50, 100 and 150%) during growth periods, the initial stage, rapid stage, mid-season stage, and late season stage were discussed at constant 100 % ETC water regime level.

Figure 9 with the levels of fertilization showed the maximum value of that the crop water stress index, and the index of stomatal conductance were 0.57 and 2.87.

Also, it was shown the minimum value for the same indices were 0.41and 1.9.

Linear regression analysis was performed to predict the CWSI and IG at different irrigation levels.

The following equations represent the relationship.

CWSI:

$y = 0.0547x + 0.367$ $R^2 = 0.9809$

IG:

$y = 0.3231x + 1.1536$ $R^2 = 0.984$

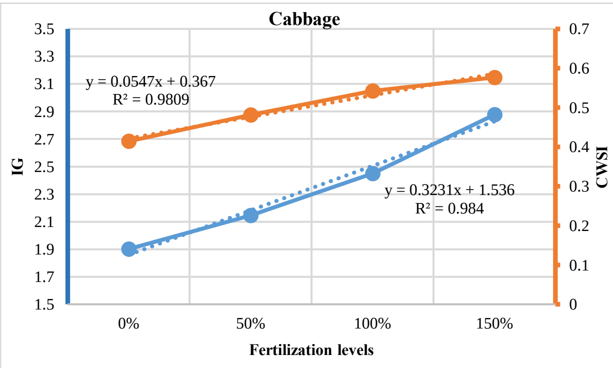


Fig. 9. Crop water stress index, and the index of stomatal conductance with fertilization levels of cabbage crop

Source: Own results.

CONCLUSIONS

The use of infrared thermography for detailed and continuous monitoring showed its ability to distinguish and show the thermal stress of plants under nitrogen deficiency and irrigation water, and to distinguish the percentages of plant contamination with heavy elements and their impact on vegetative characteristics, and to detect the heat water stress under protected greenhouse conditions in Libya.

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