Determining the emissivity of the leaves of nine horticultural crops by means of infrared thermography

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Abstract

The present study was carried out with the aim of analysing the variability of the emissivity values of nine of the most characteristic horticultural crops of the greenhouse productive system in the Mediterranean region. A thermographic camera was used for both qualitative and quantitative emissivity measurement by evaluating radiation emission from the leaves. The real temperature of the leaves was also measured with a contact probe in order to calculate emissivity. The differences in emissivity between crops for the upper side of leaves are below standard deviation values, the average values are all close to 0.98. For upper side of leaves we obtained the following average values of emissivity: 0.980±0.010 for *Lycopersicum esculentum* Mill., 0.978±0.008 for *Capsicum annuum* L., 0.983±0.008 for *Cucumis sativus* L., 0.985±0.007 for *Cucurbita pepo* L., 0.973±0.007 for *Solanum melongena* L., 0.978±0.006 for *Cucumis melo* L., 0.981±0.009 for *Citrullus lanatus* Thunb., 0.983±0.006 for *Phaseolus vulgaris* L. and 0.983±0.005 for *Phaseolus coccineus* L. Considerable differences have been observed between the emissivity values on the opposite sides of the leaves in some horticultural crops, such as green bean and particularly red bean, with a difference of 0.029 in the average emissivity value. Emissivity values of 0.98 are recommended as a reference for measuring the temperature of horticultural crops other than those studied here whenever there is no other possibility to determine the emissivity.

Keywords: Infrared thermography, crop emissivity, canopy temperature, horticultural crops.

Nomenclature

R_h	energy flux emitted by leaves, W m^{-2}
R_T	radiance entering a thermographic camera, W m^{-2}
T	object temperature, K
T_a	air temperature, K
$T_{h\text{-}0.98}$	leaf temperature measured with a thermographic camera with reference emissivity, K
T_{refl}	reflected temperature, K
T_s	leaf temperature measured with a contact probe, K
T_{sub}	water temperature measured with a submerged probe in the bath, K
T_w	water temperature measured with a thermographic camera, K
λ	wavelength, µm
σ	Stefan–Boltzmann's constant, 5.67051×10^{-8} W m^{-2} K^{-4}
ε	emissivity
ε_{ref}	reference emissivity equal to 0.98
ε_h	calculated emissivity of the leaves
τ	spectral transmittance of atmosphere

1. Introduction

Measuring the temperature of objects by infrared thermography is becoming more and more frequent in a wide variety of experimental fields, among which we should mention agriculture.

While air temperature is quite easy to measure with thermometers, thermocouples or thermistors, the measurement of crop temperature is usually more difficult to achieve, mainly when continuous non-contact measurements are necessary (Mahan and Yeater, 2008). The importance of plant temperature in agriculture was established towards the late 1970s and early 1980s (Blad and Rosenburg, 1976; Thofelt, 1977; Idso, 1982; Jackson, 1982). It was initially studied by measuring leaf temperature with micro-thermocouples (Hurd and Bailey, 1983; Caouette *et al*., 1990; and Nilsson, 1991), but this technique can be inefficient (Tanner, 1963) since these devices easily become detached (Meyer *et al*., 1994) and therefore record incorrect data. The measurement of this variable by direct contact sensors presents several problems, the most serious probably being the need for spatial integration to obtain a meaningful average (Fuchs and Tanner, 1966). Most of these problems can be overcome by measuring the thermal radiation emitted by the canopy as a whole (Berliner *et al*., 1984). Consequently, we have considered non-contact measurement of leaf temperature a more suitable technique for monitoring the temperature of vegetable crops.

Radiometric surface thermometers or infrared thermometers (IRTs) can be used to measure crop temperature. Infrared thermometers with a band pass filter from 8-13µm allowed measurement of the real temperature of plant surfaces with errors in the range of 0.1-0.3ºC (Fuchs and Tanner, 1966). The advantages of this method include the fact that there is no need for physical contact with the plant, simple automation of data collection and non-point measurements that accommodate inherent spatial variability (Mahan and Yeater, 2008).

The above technique has been used to study crop temperature in many recent studies, for example to analyse the relationship between leaf temperature and water use and growth of plants (Tanner, 1963; Jackson *et al*., 1981; Hatfield *et al*., 1983; Choudhury *et al*., 1986; Hatfield, 1990; Wanjura and Mahan, 1994; Pinter *et al*., 2003; Peters and Evett, 2004). The canopy temperature (as derived from thermal radiation measurements) and notably its relationship with selected reference variables have been used as a basis for defining stress indices (Aston and Van Bavel, 1972; Idso *et al*., 1981; Jackson *et al*., 1981). Guimaraes *et al*. (2010) evaluated the use of infrared thermometry in the characterization of inter specific and intra specific upland rice lines for drought tolerance.

Model simulations and experimental measurements were used to investigate the applicability of infrared thermography for the estimation of stomatal conductance and drought stress under sub-optimal meteorological conditions (Maes *et al*., 2011). The leaf energy balance and resulting leaf temperature are central themes of biometeorology; transpiration, sensible heat flux, photosynthesis, respiration and other metabolic activities are driven by leaf temperature (Leuzinger and Körner, 2007). The stomata play a major role in this respect, as on closing they limit the amount of energy that can be dissipated by transpiration and consequently cause the leaf temperature to increase (Raschke, 1960). Drought-induced stomatal closure causes a rise in canopy temperature that can be detected by infrared thermometers (Ehrler *et al*., 1978). Hashimoto *et al*. (1981) showed a correlation between leaf temperature and stomatal aperture using a thermal camera, and Guilioni *et al*. (2008) clarify and synthesize the appropriate equations linking the stomatal resistance of a leaf to its own temperature and to the temperatures of reference leaves (dry and wet).

The significance of leaf temperature and stomatal aperture for plant water relations was acknowledged in the early 20th century, and irrigation scheduling by means of canopy temperature surveys has been used in agriculture and horticulture since the 1960s (Fuchs and Tanner, 1966; Jackson *et al*., 1977; Fuchs, 1990; Jones, 2004). Greenhouse researchers have long been interested in measuring leaf temperatures for the purposes of estimating stomatal aperture and transpiration at canopy level, and controlling greenhouse climate (Hashimoto *et al*., 1981; Bakker, 1984; Ehret, 2001). Some methods have been developed to estimate accurately stomatal conductance from leaf temperatures (Jones, 1999; Jones *et al*., 2002; Leinonen *et al*., 2006).

Radiometric surface temperatures obtained from thermal camera measurements are a function of both the physical surface temperature and the effective emissivity of the surface within the band pass of the radiometric measurement (Humes *et al*., 1994). For accurate measurement of crop temperature by infrared radiation, the emissivity must either be known or determined, making a correction accounting for the reflected radiation from the surroundings (Fuchs and Tanner, 1966; Hipps, 1989; Sugita *et al*., 1996). The emissivity, ε, describes the ratio of radiation emitted by an object at a certain temperature, to the value emitted by a perfect emitter (Husehke, 1959). The values for emissivity may range from zero to unity. If an incorrect value is assumed, error must result (Hipps, 1989). Several field methods were developed to determine canopy emissivity in the infrared region (Fuchs and Tanner, 1966; Buettner and Kern, 1965). Most of these methods are physically sound and have been widely used for the determination of the emissivity of land surfaces (Blad and Rosenburg, 1976; Labed and Stoll, 1991; Humes *et al*., 1994).

Few studies have been carried out to determine crop emissivity. Hipps (1989) obtained a value of emissivity of 0.97 for *Artemisia tridentata* L. following the method described by Fuchs and Tanner (1966). The same method was used by Berliner *et al*. (1984), to calibrate a infrared thermometer used to estimate water stress in plants. Rahkonen and Jokela (2003) determined an emissivity of 0.98 for *Brassica rapa* L. and *Sonchus arvensis* L. with a reference emittance technique. Rubio *et al*. (1997) calculated the emissivity of a great many varieties, finding average values of $\varepsilon = 0.983 \pm 0.004$ for trees, $\varepsilon = 0.984 \pm 0.007$ for shrubs, $\varepsilon = 0.984 \pm 0.009$ for wet herbs or herbs on wet soils and $\varepsilon = 0.962 \pm 0.013$ for dry herbs or dry soils.

Given the shortage of previous studies determining the emissivity of horticultural crops such as tomato, the present study was carried out with the aim of making known emissivity values of the most characteristic crops of the productive system in the Mediterranean region. These values of emissivity are required when using the surface temperature of crops in energy balance applications (e.g. to estimate stomatal conductance, or to assess drought stress).

2. Materials and methods

2.1. Theoretical considerations

The radiance entering a thermographic camera originates from three sources (Lamprecht *et al.*, 2002): (i) the observed object itself; (ii) other objects reflected on the target's surface, and; (iii) an atmospheric contribution.

$$R_T = \varepsilon\sigma T^4 + (1-\varepsilon)\sigma T_{refl}^4 + (1-\tau)\sigma T_a^4 \qquad (1)$$

where R_T is the energy flux emitted at a wavelength of 7.3–13 μm in $\mathrm{Wm^{-2}}$, ε is the emissivity of the target (equal to 1 for a perfect emitter), σ is Stefan–Boltzmann's constant (5.67051×10^{-8} $\mathrm{W\,m^{-2}\,K^{-4}}$), $(1-\varepsilon)$ corresponds to the reflectivity, $(1-\tau)$ is the emittance of the atmosphere, T is the temperature of the target, T_{refl} is the background temperature that the target is reflecting and T_a is the air temperature, all in K.

Equation 1 addresses the two sources of error in radiative temperature measurements, namely the estimates of emissivity and background temperature. These errors in plant temperature measurements have been discussed in more detail by Sutherland and Bartholic (1979), Amiro *et al*. (1983), Hipps (1989) and Svendsen *et al*. (1990).

2.2. Experimental arrangement

The experimental configuration is shown in Fig. 1. Fresh leaves, just separated from a plant, were placed floating in a water bath.

Thermometry was performed in two ways: (i) using a thermographic camera to determine the surface temperatures of leaves and the water; and (ii) using data loggers for a continuous monitoring of air, water and leaf temperatures.

2.2.1. IR thermography

The thermographic images (Fig. 2) were recorded with a compact infrared camera ThermoVision^{TM} A40-M (FLIR Systems AB, Danderyd, Sweden), with a spectral infrared range of wavelength λ from 7.3 to 13 µm, a temperature range of –40 to +120ºC and an accuracy of ±2%. The detector was a Focal Plane Array, uncooled microbolometer of 320×240 pixels and the field of view was 24º×18º with a minimal focus distance of 0.3 m. The spatial resolution was 0.08ºC at 30ºC.

The camera is supported by the software package ThermaCAM™ Researcher Pro 2.8 SR-3 (FLIR Systems AB, Danderyd, Sweden), which offers numerous analysis functions such as point temperatures, profiles, histograms, isotherms or the determination of the maximum temperature in the image. The range of the actual temperature and the false-colours of the IR images can be chosen as desire.

2.2.2. Thermometry

The analysis requires some parameters for a correct adjustment of the temperature values. It is necessary to know the distance of the object (0.5 m), the temperature and humidity of the air, and the reflected temperature. Continuous air temperature and relativity humidity of the air were measured with two dataloggers HOBO® Pro Temp-HR U23-001 (Onset Computer Corp., Pocasset, USA) with accuracy of ±0.18ºC and ±2.5%. The temperature of the water was measured with a submerged probe HOBO® TMC6-HC (Onset Computer Corp., Pocasset, USA) with accuracy of ±0.5°C at +20ºC, besides the reading of the Thermomix bath.

For a correct calculation of the emissivity the real temperature of the leaf must be known at each moment. As a result, as well as the surface temperature of the water measured by the thermographic camera and the water temperature measured with the probe submerged in the bath, the leaf temperature was measured with a contact probe SR-TFH-DISC, Desin Instrument, S.A., Barcelona (Spain), with accuracy of ±0.4ºC at +20ºC and a measurement range of 0-150ºC (Fig. 3b). These measurements were used to study whether the surface temperature of the water obtained from thermographic images and the leaf temperature were the same.

The starting temperature of the bath was 25ºC, increasing to 45 ºC (the temperature used by Rahkonen and Jokela, 2003) at intervals of 2.5ºC. For each fixed temperature, we have registered 4 sequences of images of 3 minutes' duration with a frequency of 1 Hz, two sequences for the upper side and two for the underside of the leaves. For each of these sequences and for each temperature, two different mature leaves are collected fresh from the mid-lower part of the plant analyzed. In each sequence, 5 surfaces of the vegetable material were defined to measure the temperature. This means a total of 1800 emissivity values calculated for the upper side and underside of each horticultural crop.

2.2.3. Leaf emissivity measurement

The emissivity of the leaves was measured with the reference emittance technique described by Fuchs and Tanner (1966) and Rahkonen and Jokela (2003). Measurement was performed at ambient room temperatures of 22 ± 2°C and with water bath temperatures ranging from 25 - 45°C. A well-stirred water bath was used as a reference material (Berliner *et al.*, 1984).

Emissivity of water (λ = 8 – 12 μm) was assumed to be 0.98 (Buettner and Kern, 1965; Robinson and Davies, 1972; Pinkley *et al.*, 1977; Zhang *et al.*, 1986; Salisbury and Milton, 1988). The background radiation level was measured by using an aluminium foil inserted near the water surface as a reflector. The radiation levels of a reference surface (water as reference material) and a leaf carefully lowered to float on the water were measured. This method assumed that the temperature of the water and the leaf is the same.

The following procedure was used to determine the emissivity of the vegetable material: freshly picked leaves were placed floating on the water in the bath which had been heated to the given temperature. A certain time (in about 1 minute) was left before starting to record images in order to ensure that the temperature of the leaf and of the water was the same. Thermographic images were stored (Fig. 2) for three minutes at a frequency of one image per second (1 Hz). From the sequence of images obtained and using the ThermaCAM™ Researcher Pro 2.8 SR-3 software several analyses were carried out.

Firstly, the average values of air temperature and humidity in each sequence of images are introduced so that the software can calculate the fraction of radiation emitted by the atmosphere. The emittance of the atmosphere, $(1-\tau)$, which is heavily dependent on the relative humidity of the air. In this way the software estimates τ (FLIR, 2006).

Secondly, it is necessary to calculate the fraction of radiation reflected by the leaves. A sheet of aluminium foil was placed on one side over the water bath. Aluminium foil has very low emissivity and acts as a reflector. By setting the emissivity to 1 in the image analysis software for the area of the aluminium foil (Fig. 1) and carrying out a first analysis of the images, the average value of the reflected temperature is obtained (T_{refl}).

Once we know the reflected temperature, air temperature and humidity and the distance from the camera to the water bath (0.5 m), a second image analysis is carried out to determine the water temperature (T_w) with emissivity 0.98, and the temperature of the leaves ($T_{h\text{-}0.98}$) also with a reference emissivity of 0.98.

From the analysis carried out on the surface of the leaves, the following expression is obtained:

$$R_h = \varepsilon_{ref}\sigma T_{h\text{-}0.98}^4 + \left(1-\varepsilon_{ref}\right)\sigma T_{refl}^4 + \left(1-\tau\right)\sigma T_a^4 \qquad (2)$$

where R_h is the energy flux emitted by the leaves at a wavelength of 7.3–13 μm in $\mathrm{Wm^{-2}}$, and $T_{h\text{-}0.98}$ is the temperature of the target, for a reference emissivity of $\varepsilon_{ref} = 0.98$.

The total radiation reaching the camera focussing on the leaves can be expressed as a function of the real emissivity of the leaves (ε_h), the unknown that is the object of study, and the real temperature of the leaves, assuming that the water bath and the leaves are at the same temperature, which would be T_w:

$$R_h = \varepsilon_h\sigma T_w^4 + \left(1-\varepsilon_h\right)\sigma T_{refl}^4 + \left(1-\tau\right)\sigma T_a^4 \qquad (3)$$

From equations 8 and 9 we obtain the expression which allows the real emissivity of the leaves, ε_h, to be calculated:

$$\varepsilon_h = \varepsilon_{ref} \cdot \left(T_{h\text{-}0.98}^4 - T_{refl}^4\right) / \left(T_w^4 - T_{refl}^4\right) \qquad (4)$$

For the water bath a rectangular plastic container (42×25×16 cm) was used. The leaves stay floating in the water on a metallic grill, which ensures that the leaves do not move outside the camera’s focal range. The temperature of the well-stirred water was controlled with a

Thermomix® BM agitator (Braun Biotech International, Melsungen, Germany), which has a working range of 22-100ºC and an accuracy of ±0.03ºC.

2.3. Thermal image analysis

Several different thermal analyses were performed using the ThermaCAM™ Researcher Pro 2.8 SR-3 digital infrared thermal image processing software. Due to the large amount of measurement data, not all the material was included in each analysis. The different analyses and the materials used in each are listed below.

Emissivity data were subjected to Analysis of Variance (ANOVA) using Statgraphics Plus 4.1 Software (Manugistics, Inc., Rockville, MD, USA). One-way ANOVA and possible significant differences between the emissivity values were evaluated by Least Significant Differences (LSD) multiple comparison tests with a confidence level of 95%.

2.3.1. Temporal and spatial variation in temperature

Temporal variation in temperature was analysed by the average temperature of a selected area (Fig. 3a) of a leaf versus time at a maximum sample rate of 1 Hz over 3 min (180 values of emissivity). Spatial variation in temperature was analysed by capturing thermal images at five moments during the experiments for every crop leaf. Linear temperature distributions were studied by creating line graphs (Fig 3a) describing temperatures (80 values) along a line crossing a leaf.

2.3.2. Emissivity variation among leaves

For each crop, the emissivity values of the upper and lower sides of four different groups of leaves were determined independently for bath temperatures from 35ºC to 45ºC (for each group have been used five leaves, one for each water bath temperature). These values (900 values for each group of leaves) then underwent statistical analysis to determine the variation in emissivity among groups of leaves.

2.4. Vegetable materials

The horticultural crops studied in this work were tomato (*Lycopersicum esculentum* Mill.), green pepper (*Capsicum annuum* L.), cucumber (*Cucumis sativus* L.), courgette (*Cucurbita pepo* L.), aubergine (*Solanum melongena* L.), melon (*Cucumis melo* L.), watermelon (*Citrullus lanatus* Thunb.), green bean (*Phaseolus vulgaris* L.) and red bean (*Phaseolus coccineus* L.).

3. Results and discussions

Firstly we have studied the difference between the temperature of the leaves floating in the water bath, obtained by the thermographic camera, and the temperature of the water as detected by the sensor and by the thermographic camera. This was followed by a study of the temporal and spatial variation of the leaf temperature during the assays. Finally the emissivity for the nine horticultural species was calculated. Differences were detected between species and between the upper and lower sides of the leaf of given species, and the results obtained were compared with the values of emissivity found in the literature for each type of vegetable matter.

3.1. Difference between leaf and water temperature

The values of leaf temperature, measured with the contact sensor, and water temperature, obtained by the thermographic camera, were very similar (Table 1). The maximum difference observed was 0.21ºC. In all cases the differences detected were less than the accuracy margin of the thermographic camera (2%). If the leaves are maintained floating on the water bath at a constant temperature for a prudent length of time (3-5 min) before commencing the assay, it can be assumed that the leaf and water temperature measured by the thermographic camera is the same, and therefore the emissivity of the leaves can be determined using the water as reference material.

The slight differences in temperature observed may be due to the difficulty in placing the contact sensor correctly on the irregular leaf surface. It is precisely this difficulty that is the main reason why not all the assays were carried out with the contact sensor on the leaves.

Another drawback found when using the contact temperature sensor is the fine layer of hairs on the top and/or underside of the leaves of some of the crops studied, for instance aubergine. In addition, the sensor is not easy to handle. It consists of a 15 mm diameter metal disc connected to a PC by a rather inflexible cable. It was fixed to the leaves using adhesive tape to ensure the best contact possible. It was then placed on the water bath, taking care that the leaf was in full contact with the water, but also that the sensor did not get wet. The rigidity of the cable made this task almost impossible and many assays were invalidated because of this. On other occasions, once the assays had been completed, small fissures were found to have been made in the leaves by the sensor disc, meaning that the sensor had got wet, and these assays were also fruitless.

To determine the emissivity of the leaves we have used the surface temperature of the water instead of the underwater temperature. The surface temperature is less than the underwater temperature, as it could be affected by evaporative cooling and sensible heat exchange with the environment. Table 1 shows the average temperature values recorded by the thermographic camera and by the submerged temperature sensor during the assays with pepper leaves. As the temperature of the water bath increases from 25 to 45ºC, so does the difference between both increases from 0.08% to -4.91%. As we can observe in Table 1 the water temperatures measured with the submerged sensor are very close to the set-point temperatures showed by the Thermomix® BM agitator. We can also observe that these set-point temperatures of the water bath are greater than the leaf temperatures and the surface water temperatures. So is very important to emphasize that the set-point temperature is not appropriate as reference temperature for the leaves.

3.2. Temporal and spatial temperature variation in leaves

The highest temporal variation in leaf temperature was observed at the lowest water bath temperature (25ºC), which is very close to ambient temperature. In the cases of greatest variation, the leaf temperature was 25.22 ± 0.12ºC.

The spatial temperature variation was acceptable for all crops, the greatest spatial variation in leaf temperature (40.72 ± 0.15ºC) was observed for an image taken with the water bath at 42.5ºC, and the lowest (34.16 ± 0.08ºC) at 35ºC.

Although the spatial variation was slightly greater than the temporal variation, in both cases the dispersion or variation in leaf temperature obtained by this method is acceptable, being less than the accuracy margin of the thermographic camera.

3.3. Emissivity of the crops

Tables 2 and 3 show the emissivity values obtained at different water bath temperatures.

Rahkonen and Jokela (2003) set the temperature of the bath of water at 45ºC to determine the emissivity of *Brassica rapa* L. and *Sonchus arvensis* L. In the present work we have used a wider range of temperatures in order to analyse the influence of temperature on emissivity variations. We have observed that the emissivity values calculated using bath temperatures close to ambient temperature are not accurate with a great dispersion (Fig. 4), and greater temporal leaf temperature variation is also observed. When the temperature of the bath was close to ambient temperature (25ºC and 27.5ºC), the quantity of radiation emitted by the vegetable material was similar to the radiation emitted by the water. In these conditions, the thermographic camera does not obtain a clear image of leaves. Figure 5 illustrates the difference in clarity between a thermographic image taken at a water temperature of 25ºC and one at 37.5ºC. Other authors also observed dispersion in temperature values during the calibration of infrared thermometers with water bath temperatures close to ambient values (Churchill *et al*. 1982; Berliner *et al*. 1984).

For water temperature close to air temperature we obtained emissivity close to 1 for all crops analysed, as can be observed in Fig. 4, which shows the dispersion of the emissivity values calculated for the upper side of cucumber leaves of and the underside of courgette leaves.

For higher bath temperatures, the dispersion of the values of calculated emissivity is very low, as all are very near the average value. Also these values were very similar between temperatures and for images with the same water temperature (Fig. 4).

The greater radiation emitted by the material at these temperatures allows a correct calculation of the emissivity. For this reason, we have only considered the emissivity values obtained for bath temperatures from 35ºC to 45ºC. It is recommendable to use bath temperatures that are at least 15ºC above the ambient temperature.

The average values of emissivity obtained in the present study correspond to the spectral range of the thermographic camera, between 7.3 and 13 µm.

The emissivity values obtained (Table 4) for most of the crops under study are very similar to those considered by other authors (Table 5). Brewster (1992) and Meyer *et al*. (1994) use emissivity of $\varepsilon = 0.98$ as generic for different vegetables. Hipps (1989) obtained emissivity of $\varepsilon = 0.97$ for *Artemisia tridentata* L. following the method established by Fuchs and Tanner (1966). Rahkonen and Jokela 2003 determined the emissivity of *Brassica rapa* L. and *Sonchus arvensis* L. ($\varepsilon = 0.98$) with a reference emittance technique also using a well-stirred water bath at a temperature of about 45ºC. Rubio *et al*. (1997) calculated the emissivity of a great many varieties, finding average values of $\varepsilon = 0.983 \pm 0.004$ for trees, $\varepsilon = 0.984 \pm 0.007$ for shrubs, $\varepsilon = 0.984 \pm 0.009$ for wet herbs or herbs on wet soils and $\varepsilon = 0.962 \pm 0.013$ for dry herbs or dry soils.

3.4. Emissivity variation among leaves

Although in some crops statistically significant differences were found between the emissivity of different groups of leaves (Table 6), on the whole the maximum differences recorded were less than 0.001. This value was only surpassed for the underside of the leaves of three crops (tomato, courgette and red bean), and the maximum difference recorded was 0.0018 for courgette. This statistical analysis indicates that the number of leaves and replications in the experiments provides sufficient accuracy in obtaining the emissivity values.

3.5. Difference between the upper side and the underside of the leaves

Tomato was the only vegetable for which no statistical differences were found between the emissivity on opposite sides of the leaf (Fig. 6a). The results of other vegetables in ascending order of differences in emissivity between the opposite sides of the leaf were courgette, cucumber (Fig. 6b) and melon, for which the difference were significant (≤0.003) but less than the standard deviation of the emissivity values calculated. A second group consisted of water melon (Fig. 6c) and aubergine, with differences in average values of 0.004 and 0.005 respectively, also less than the standard deviation. Finally, pepper, green bean and red bean showed greater differences between the emissivity of opposite sides of the leaf. Green and red bean in particular (Fig. 6d), for which the differences in the average values were 0.015 and 0.029, respectively, and these values are greater than the standard deviation. The different emissivity values observed between the opposite sides of the leaf may in part be due to the different tones of the upper side and underside. Red bean is one of the crops where this difference in tonality is most notable (Fig. 7).

Considerable differences have been observed between the emissivity values on the opposite sides of the leaves in some horticultural crops, such as the green bean, and particularly the red bean, with a difference in the average emissivity value of 0.029 (Table 4). For future works, in which researchers wish to evaluate or control the temperature of horticultural crops carrying out measurements of radiation emission in the infrared range, special consideration should be given to these crops.

We have estimated the possible error as a result of not correcting for the difference in emissivity between the upper side and underside of leaves of red bean. For instance, at leaf temperature equal to 25ºC measured for a recommended emissivity of 0.98 and reflected temperature equal to 270 K, this error would be 0.74ºC. Leaf temperature would be 24.93°C (emissivity 0.983) and 25.66°C (emissivity 0.954) for the upper side and underside of leaves, respectively.

Any image taken of a real crop in the greenhouse is most likely to include both upper sides of some leaves and the undersides of others. This makes later analysis extremely complicated as it is most difficult to differentiate which areas of the image correspond to which side of the leaf. Figure 8 shows a thermographic image of a tomato crop taken inside a greenhouse. It would be impossible to tell apart the two sides of the leaves unless there were some reference points located on the leaves.

3.6. Variations between crops.

In order to determine the differences in emissivity between crops, the values obtained from 35ºC and above in the water bath have been analysed statistically. Figure 9 shows the results of this analysis for the upperside on the one hand, and for the underside on the other.

The differences in emissivity between crops for the upper side of leaves are below standard deviation values. The average values are all close to 0.980, and range from 0.973 (minimum value, for aubergine leaves) to 0.985 (for cucumber leaves).

Greater differences in emissivity were observed between crops for the underside of leaves (Fig. 9b). Particularly noteworthy are red bean, green bean and aubergine, with emissivity values well below 0.980. For the remaining crops, as occurred for the upper side of leaves, all the average values are close to 0.980, ranging from 0.980 (melon) to 0.987 (pepper), with differences below standard deviation values.

For the monitoring of temperature using infrared thermography within the spectral range 7.3-13 µm, a reference emissivity value of 0.980 is recommended for horticultural crops other than those studied here. However, when infrared thermography is used as a technique to determine the temperature of crops for experimental purposes requiring greater accuracy, the method described in the present paper is recommended.

4. Conclusions.

The method described maintains the temperature of the leaves within a very small interval during assays, with very low spatial variation (<0.7ºC), and temporal variation (<0.4ºC).

The reference temperature to be considered to calculate the emissivity of leaves is the surface temperature of the water bath measured with the thermographic camera. The temperature values below the water surface were not valid for this method.

A wide range of emissivity values were recorded at water bath temperatures close to ambient temperature. Water bath temperatures of at least 15ºC above ambient temperature are recommended.

The emissivity values of the upper sides of leaves of the crops studied were very close to 0.980, and no significant differences were observed among the nine crops. For the underside of leaves significant differences were found in three of the species, with emissivity values somewhat below 0.980: green pepper, green bean and red bean. In the same three species significant differences were also detected between the emissivity of the upper and the lower sides of the leaves.

Emissivity values of 0.98 are recommended as a reference for measuring the temperature of horticultural crops other than those studied here whenever there is no other possibility to determine the emissivity.

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Figure captions

Figure 1. Experimental arrangement for measuring emissivity of one side of a plant leaf by imaging infrared thermography while the other side is floating in a water bath.

Figure 2. Analysis of a thermographic image for a water temperature of 37.5ºC with 7 selected areas: 5 distributed in 2 aubergine leaves, 1 to define the water bath and 1 to measure the temperature reflected by the aluminium sheet.

Figure 3. Area selected for analysis of temporal variation and the transversal line for the analysis of spatial variation (a). Thermographic image of the contact temperature sensor on a tomato leaf (b).

Figure 4. Emissivity values calculated for the upper side of cucumber leaves (a) and for the underside of courgette leaves (b).

Figure 5. Images of the upper side of aubergine leaves floating on the bath of water at 25ºC (a) and 37.5ºC (b).

Figure 6. Statistical analysis of the emissivity values of the upper side and underside of the leaves of tomato (a), cucumber (b), water melon (c) and red bean (d).

Figure 7. Leaves of red bean floating in the water bath: upper side (a) and underside (b).

Figure 8. Thermographic image of a tomato crop taken at midday.

Figure 9. Emissivity of the upper side of leaves (a) and of the underside (b) of nine horticultural crops.

Tables

Table 1. Temperature of the water bath calculated from the thermographic images (T_w); temperature of the leaves measured with the contact sensor (T_s); water temperature measured with the submerged sensor (T_{sub}).

	Thermomix® BM Temperature Setpoint (ºC)					
	40.0	**40.0**	**45.0**	**45.0**	**45.0**	**45.0**
T_w (ºC)	37.90	37.71	42.06	41.93	42.08	42.08
T_s (ºC)	37.79	37.50	41.88	41.84	42.03	42.05
$(T_w – T_s)/T_w$ (%)	0.29	0.56	0.43	0.21	0.12	0.07

	Thermomix® BM Temperature Setpoint (ºC)								
	25.0	**27.5**	**30.0**	**32.5**	**35.0**	**37.5**	**40.0**	**42.5**	**45.0**
T_w (ºC)	25.18	27.59	29.70	31.93	34.16	36.35	38.57	40.77	42.79
T_{sub} (ºC)	25.16	27.52	29.94	32.74	35.17	37.44	40.13	42.46	44.89
$(T_w – T_{sub})/T_w$ (%)	0.08	0.25	-0.81	-2.54	-2.96	-3.00	-4.04	-4.15	-4.91

Table 2. Emissivity values (average value ± standard deviation) of the upperside of the leaves of nine horticultural crops obtained by the method of the reference material for 9 different water bath temperatures.

upper side	Thermomix® BM Temperature Setpoint (ºC)				
	35.0	**37.5**	**40.0**	**42.5**	**45.0**
Tomato	0.978 ± 0.010	0.980 ± 0.009	0.979 ± 0.009	0.982 ± 0.007	0.982 ± 0.011
Pepper	0.978 ± 0.008	0.977 ± 0.008	0.977 ± 0.007	0.978 ± 0.008	0.977 ± 0.007
Cucumber	0.982 ± 0.010	0.982 ± 0.006	0.982 ± 0.007	0.986 ± 0.007	0.984 ± 0.010
Courgette	0.986 ± 0.007	0.985 ± 0.007	0.985 ± 0.007	0.986 ± 0.008	0.983 ± 0.007
Aubergine	0.971 ± 0.006	0.971 ± 0.007	0.974 ± 0.007	0.973 ± 0.008	0.975 ± 0.007
Melon	0.978 ± 0.006	0.978 ± 0.006	0.980 ± 0.006	0.979 ± 0.005	0.977 ± 0.007
Watermelon	0.982 ± 0.009	0.981 ± 0.009	0.980 ± 0.008	0.978 ± 0.010	0.982 ± 0.009
Grean bean	0.982 ± 0.007	0.984 ± 0.006	0.983 ± 0.024	0.981 ± 0.006	0.983 ± 0.006
Red bean	0.983 ± 0.005	0.983 ± 0.005	0.982 ± 0.005	0.983 ± 0.005	0.985 ± 0.005

Table 3. Emissivity values (average value ± standard deviation) of the underside of the leaves of nine different horticultural crops obtained by the method of the reference material for 9 different water bath temperatures.

underside	Thermomix® BM Temperature Setpoint (ºC)				
	35.0	**37.5**	**40.0**	**42.5**	**45.0**
Tomato	0.982 ± 0.008	0.977 ± 0.008	0.980 ± 0.007	0.985 ± 0.011	0.979 ± 0.010
Pepper	0.983 ± 0.007	0.985 ± 0.006	0.992 ± 0.007	0.994 ± 0.007	0.983 ± 0.006
Cucumber	0.985 ± 0.010	0.986 ± 0.009	0.985 ± 0.009	0.988 ± 0.008	0.986 ± 0.008
Courgette	0.984 ± 0.008	0.986 ± 0.007	0.981 ± 0.008	0.985 ± 0.006	0.982 ± 0.008
Aubergine	0.966 ± 0.008	0.966 ± 0.009	0.969 ± 0.009	0.968 ± 0.008	0.970 ± 0.008
Melon	0.984 ± 0.008	0.981 ± 0.005	0.981 ± 0.004	0.979 ± 0.005	0.978 ± 0.005
Watermelon	0.986 ± 0.011	0.986 ± 0.009	0.985 ± 0.008	0.983 ± 0.009	0.984 ± 0.008
Grean bean	0.976 ± 0.017	0.969 ± 0.009	0.965 ± 0.012	0.967 ± 0.016	0.961 ± 0.015
Red bean	0.951 ± 0.012	0.954 ± 0.008	0.957 ± 0.013	0.952 ± 0.008	0.958 ± 0.012

Table 4**.** Emissivity values (average value ± standard deviation) for the leaves of the nine crops analysed calculated using the temperature of the water measured with the thermographic camera (from 35 to 45ºC).

	Crops	*upper side*	*underside*
Tomato	*Lycopersicum esculentum* Mill.	0.980 ± 0.010	0.981 ± 0.009
Pepper	*Capsicum annuum* L.	0.978 ± 0.008	0.987 ± 0.008
Cucumber	*Cucumis sativus* L.	0.983 ± 0.008	0.986 ± 0.009
Courgette	*Cucúrbita pepo* L.	0.985 ± 0.007	0.984 ± 0.008
Aubergine	*Solanum melongena* L	0.973 ± 0.007	0.968 ± 0.008
Melon	*Cucumis melo* L.	0.978 ± 0.006	0.980 ± 0.006
Watermelon	*Citrullus lanatus* Thunb.	0.981 ± 0.009	0.985 ± 0.009
Green Bean	*Phaseolus vulgaris* L.	0.983 ± 0.006	0.968 ± 0.015
Red Bean	*Phaseolus coccineus* L.	0.983 ± 0.005	0.954 ± 0.011

Table 5. Emissivity values obtained by several authors for different plants.

Crops		*Emissivity*	*Source*
Snap bean	*Phaseolus vulgaris* L.	0.96	Fuchs and Tanner, 1966
Tobacco	*Nicotiana tabacum* L.	0.97	Fuchs and Tanner, 1966
Artemisia	*Artemisia tridentata* L.	0.97	Hipps, 1989
Alfalfa	*Medicago sativa* L.	0.97 - 0.98	Fuchs and Tanner, 1966
Sudangrass	*Sorghum vulgare* var. sudanense Hitchc.	0.97 - 0.98	Fuchs and Tanner, 1966
Rape	*Brassicca rapa* L.	0.98 ± 0.01	Rahkonen and Jokela, 2003
Sow-thistle	*Sonchus arvensis* L.	0.98 ± 0.01	Rahkonen and Jokela, 2003
Mango	*Manginefara indica* L.	0.96	Arp and Phinney, 1980
Pine	*Pinus leiophylla* Schlecht. and Cham.	0.982 ± 0.009	Arp and Phinney, 1980
Olive	*Olea europea* L.	0.976 ± 0.006	Rubio *et al*., 1997
Alfalfa	*Medicago sativa* L.	0.987 ± 0.004	Rubio *et al*., 1997
Pine	*Pinus nigra* Arnold.	0.982 ± 0.009	Rubio *et al*., 1997
Holm Oak	*Quercus ilex* L.	0.985 ± 0.010	Rubio *et al*., 1997

Table 6. Emissivity values (average value ± standard deviation) obtained for different groups of leaves for upper side and underside of the nine crops analysed (for each group have been used five leaves, one for each water bath temperature from 35 to 45ºC).

Crop	**Underside**				
	Group of leaves 1	**Group of leaves 2**	**Group of leaves 3**	**Group of leaves 4**	**maximum difference between leaves**
Tomato	$0.980 \pm 0.013^{a,b}$	0.981 ± 0.009^{b}	0.980 ± 0.007^{b}	0.980 ± 0.007^{a}	0.0009
Pepper	0.978 ± 0.005^{a}	$0.978 \pm 0.008^{a,b}$	0.979 ± 0.006^{b}	$0.978 \pm 0.010^{a,b}$	0.0007
Cucumber	0.983 ± 0.003^{a}	0.983 ± 0.005^{a}	0.983 ± 0.007^{b}	0.983 ± 0.009^{a}	0.0009
Courgette	$0.985 \pm 0.003^{a,b}$	$0.985 \pm 0.006^{a,b,c}$	0.985 ± 0.007^{c}	0.984 ± 0.004^{a}	0.0004
Aubergine	0.973 ± 0.014^{a}	0.973 ± 0.013^{a}	0.973 ± 0.007^{a}	0.973 ± 0.007^{a}	0.0004
Melon	0.977 ± 0.003^{a}	0.978 ± 0.006^{b}	0.977 ± 0.010^{a}	0.978 ± 0.006^{b}	0.0006
Watermelon	0.981 ± 0.005^{a}	0.981 ± 0.008^{a}	0.982 ± 0.014^{a}	0.981 ± 0.009^{a}	0.0004
Grean bean	0.983 ± 0.005^{a}	0.983 ± 0.005^{a}	0.983 ± 0.008^{a}	0.983 ± 0.006^{a}	0.0003
Red bean	0.983 ± 0.004^{b}	0.983 ± 0.006^{b}	0.983 ± 0.008^{b}	0.982 ± 0.003^{a}	0.0007
Crop	**Upper side**				
	Group of leaves 1	**Group of leaves 2**	**Group of leaves 3**	**Group of leaves 4**	**maximum difference between leaves**
Tomato	0.981 ± 0.010^{b}	0.981 ± 0.007^{b}	0.980 ± 0.008^{a}	0.981 ± 0.009^{b}	0.0016
Pepper	$0.987 \pm 0.006^{a,b}$	0.987 ± 0.008^{b}	0.986 ± 0.006^{a}	$0.987 \pm 0.007^{a,b}$	0.0007
Cucumber	0.986 ± 0.004^{a}	0.986 ± 0.006^{b}	0.985 ± 0.005^{a}	0.986 ± 0.008^{a}	0.0010
Courgette	0.984 ± 0.006^{c}	0.985 ± 0.009^{c}	0.984 ± 0.011^{b}	0.983 ± 0.004^{a}	0.0018
Aubergine	0.968 ± 0.008^{a}	0.968 ± 0.011^{a}	0.968 ± 0.005^{a}	0.968 ± 0.008^{a}	0.0003
Melon	$0.980 \pm 0.006^{a,b}$	0.980 ± 0.006^{a}	$0.980 \pm 0.006^{a,b}$	0.980 ± 0.006^{b}	0.0005
Watermelon	0.984 ± 0.010^{a}	0.985 ± 0.008^{b}	$0.985 \pm 0.009^{a,b}$	0.985 ± 0.008^{b}	0.0010
Grean bean	$0.968 \pm 0.012^{a,b}$	$0.968 \pm 0.015^{a,b}$	0.968 ± 0.016^{b}	0.967 ± 0.015^{a}	0.0009
Red bean	$0.954 \pm 0.007^{a,b}$	$0.954 \pm 0.008^{a,b}$	0.954 ± 0.012^{b}	0.953 ± 0.014^{a}	0.0011

Within each line, the levels containing the same letter form a group of means within which there are no statistically significant differences (95% confidence level).