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REVIEW PAPER

Applications of Thermal Imaging in Agriculture and Food Industry—A Review

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Abstract Thermal imaging is a technique to convert the invisible radiation pattern of an object into visible images for feature extraction and analysis. Infrared thermal imaging was first developed for military purposes but later gained a wide application in various fields such as aerospace, agriculture, civil engineering, medicine, and veterinary. Infrared thermal imaging technology can be applied in all fields where temperature differences could be used to assist in evaluation, diagnosis, or analysis of a process or product. Potential use of thermal imaging in agriculture and food industry includes predicting water stress in crops, planning irrigation scheduling, disease and pathogen detection in plants, predicting fruit yield, evaluating the maturing of fruits, bruise detection in fruits and vegetables, detection of foreign bodies in food material, and temperature distribution during cooking. This paper reviews the application of thermal imaging in agriculture and food industry and elaborates on the potential of thermal imaging in various agricultural practices. The major advantage of infrared thermal imaging is the non-invasive, non-contact, and non-destructive nature of the technique to determine the temperature distribution of any object or process of interest in a short period of time.

Keywords Infrared radiation · Thermal imaging · Quality · Agriculture · Food

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Introduction

Temperature measurement is an important aspect in any industrial process and infrared thermography has revolutionized the concept of temperature measurement. Temperature measurements were generally performed using thermometers, thermocouples, thermistors, and resistance temperature detectors. These instruments can only determine temperature at specific points and most of these instruments need to establish a contact with the material. While infrared thermal imaging is a non-contact, non-destructive technique which provides temperature mapping of the material. Hence, use of infrared thermal imaging is widely increasing in many fields. All objects above 0 K (−273.15°C) emit infrared rays which are part of the electromagnetic spectrum. Electromagnetic spectrum comprises of radio waves, microwaves, infrared rays, visible light, ultraviolet rays, X-rays, and gamma rays (Fig. 1). The wavelength of infrared rays is in the range of 0.78–1,000 μm. The infrared region is further divided into different regions: near infrared (0.75–3 μm), mid infrared (3–6 μm), far infrared (6–15 μm), and extreme infrared (15–1,000 μm); (Meola & Carlomagno 2004). The intensity of radiation emitted by an object is a function of its surface temperature, i.e., the higher the temperature of the body, the greater is the intensity of infrared radiation emitted by the object. Thermal imaging is a technique which converts this radiation emitted by an object into temperature data without establishing contact with the object.

Thermal imaging has a wide application in various fields such as civil engineering, industrial maintenance, aerospace, medicine, pharmacy, and veterinary. The application of thermal imaging is gaining popularity in agriculture and food industry in recent years. The major advantages of thermal imaging are non-contact, non-invasive, and rapid

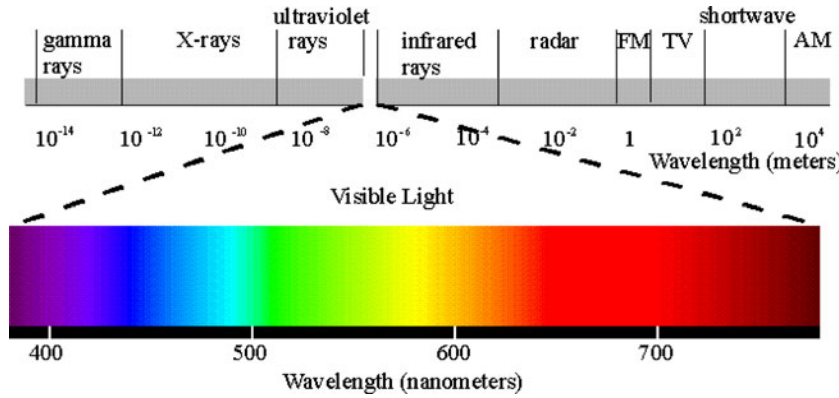


Fig. 1 Electromagnetic spectrum (Kaiser 1996)

technique which could be used for online applications. The thermal cameras are easy to handle and highly accurate temperature measurements are possible. With the thermal imaging, it is possible to obtain temperature mapping of any particular region of interest with fast response times which is not possible with thermocouples or other temperature sensors which can only measure spot data. Repeatability of temperature measurements is high in thermal imaging. Also, thermal imaging does not require an illumination source unlike other imaging systems. Previous models of thermal camera's required cryogenically cooled sensors to obtain temperature resolution of 0.1 °C whereas recent day cameras can operate at room temperature making these cameras user friendly and promoting an increase in the use of thermal imaging in various fields.

The objective of this paper is to review and summarize the potential applications of thermal imaging in various aspects of agriculture and food industry.

Thermal Imaging System

Infrared thermal imaging system comprises of thermal camera equipped with infrared detectors, a signal processing unit and an image acquisition system, usually a computer. The infrared detectors absorb the infrared energy emitted by the object and convert it into an electrical impulse. The electrical impulse is sent to the signal processing unit which translates the information into thermal image. Most of the thermal imaging devices scan at a rate of 30 times per second and can sense temperature ranging from −20 to 1,500 °C, but the temperature range can still be increased by using filters (Meola & Carlomagno 2004). Detectors are the most important part of thermal imaging system which converts the radiant energy into electrical signals proportional to the amount of radiation falling on them. There are two types of detectors: thermal and photon detectors. In thermal detectors, infrared radiation heats up the detector element resulting in temperature rise, which is taken as a measure of the radiation falling on the object. In photon detectors, incident radiation interacts at an atomic or molecular level with the material of the detector to produce charge carriers that generate a voltage across the detector element or a change in its electrical resistance. The various types of photon detectors used are cadmium mercury telluride (CMT), indium antimonide, platinum silicide, and Quantum well devices. Among the two types, photon detectors provide greater sensitivity than thermal detectors (Willimas 2009).

Thermal imaging devices can be classified into uncooled and cooled (Sierra Pacific Innovations http://www.x20.org/thermal/thermal_weapon_sight.htm). Uncooled thermal imaging device is the most common one and the infrared detector elements are contained in a unit that operates at room temperature. They are less expensive but their resolution and image quality tend to be lower than the cooled device. In the cooled thermal imaging device, the sensor elements are contained in a unit which is maintained below 0 °C. They have a very high resolution and can detect temperature difference as low as 0.1 °C but they are expensive (Sierra Pacific Innovations http://www.x20.org/thermal/thermal_weapon_sight.htm). Cooled thermal imaging devices are used in military and aerospace applications. An infrared imaging system is evaluated based on thermal sensitivity, scan speed, image resolution, and intensity resolution. Table 1 describes the specifications of the thermal camera used in various studies discussed in this paper.

Applications of Thermal Imaging in Agriculture

Thermal imaging has a potential application in many operations involved in agriculture, starting from assessing the seedling viability, estimating soil water status, estimating crop water stress, scheduling irrigation, determining disease and pathogen affected plants, estimating fruit yield, and evaluating maturity of fruits and vegetables. This section elaborates on studies conducted to determine potential use of thermal imaging in agriculture. Table 2 describes the applications of thermal imaging in agriculture.

Table 1 Details of infrared thermal cameras used in various agriculture and food-related studies

Camera model	Manufacturer	Spectral range, μm	Temperature range	Thermal sensitivity	Detector type	Image size	Frame rate	References
AGEMA 570	FLIR Systems, Oregon, USA	8–12	−20°C to 500°C; −20°C to 1,500°C (with filter)	0.1°C at 30°C	FPA, uncooled microbolometer	320×240	60 Hz	Stajnko et al. (2004)
AGEMA 880 LW	FLIR Systems, Oregon, USA	8–12	−20°C to 1,500°C	0.7 K at 30°C	HgCdTe, liquid nitrogen, or stirling cooled	NA	25 Hz	Offerman et al. (1998)
Infra-Eye 102A	Fujitsu, Tokyo, Japan	8–14	NA	NA	HgCdTe, liquid nitrogen cooled	NA	NA	Danno et al. (1977); Danno et al. (1980)
Inframetrics Model 760	Inframetrics, Massachusetts, USA	8–12	−20°C to 400°C; 20°C to 1,500°C (with filter)	0.1°C at 30°C	HgCdTe, stirling cooled	NA	30 Hz	Fuller and Wisniewski (1998); Pearce and Fuller (2001)
IR Snapshot 525	Alpine Components, East Sussex, UK	8–12	0°C to 350°C; −50°C to 650°C	0.1°C at 30°C	Uncooled	120×120	NA	Stoll and Jones (2007)
Model D500	Raytheon Inc., Waltham, MA	7–14	NA	NA	NA	320×240	NA	Catarame et al. (2003)
ThermaCam P25	FLIR Systems, Italy	7.5–13	−40°C to 120°C; 0°C to 500°C; optional: 2,000°C	0.08°C at 30°C	FPA, uncooled microbolometer	320×240	50–60 Hz	Nanni Costa et al. (2007)
ThermaCam P65HS	FLIR Systems, Oregon, USA	7.5–13	−40°C to 120°C ; 0°C to 500°C; optional: 2,000 °C	0.5 K at 30°C	FPA, uncooled microbolometer	320×240	50–60 Hz	Bulanon et al. (2008)
ThermaCam™ PM390; ThermaCam PM250	FLIR Systems, Oregon, USA; FLIR Systems; Massachusetts, USA	3.4–5	−10°C to 450°C; −20°C to 1,500°C (with filter)	0.07°C at 30°C	Platinum silicide; Stirling cycle	256×256	60 Hz	Merlot et al. (2002); Varith et al. (2003)
ThermaCAM SC500	FLIR Systems, Ontario, Canada	7.5–13	−20°C to 500°C optional: 2,000°C	0.07 K at 30°C	FPA, uncooled microbolometer	320×240	50 Hz	Hellebrand et al. (2006); Manickavasagan et al. (2008a; 2008b)
ThermaCAM SC545	FLIR Systems, Oregon, USA	7.5–13	−20°C to 350°C optional: 1,000°C	0.1°C at 30°C	FPA, uncooled microbolometer	320×240	50–60 Hz	Hellebrand et al. (2006)
ThermaCAM SC2000	FLIR Systems, Oregon, USA	7.5–13	−40°C to 2,000°C	0.1°C at 30°C	FPA, uncooled microbolometer	320×240	50–60 Hz	Sela et al. (2007)
TH7102MX	NEC, Tokyo, Japan	8–14	−40°C to 2,000°C	0.08°C at 30°C	Uncooled FPA	320×240	60 Hz	Stoll et al. (2008)
Thermosensorik CMT 384 SM/M	Thermosensorik GmbH, Germany	1.5–5 and 3.4–5.0	NA	NA	HgCdTe, stirling cooled	384×288	50–60 Hz	Warmann and Märgner, (2005); Ginesu et al. (2004)
Thermovision A40M	FLIR Systems, Danderyd, Sweden	7.5–13	−40°C to 120°C ; 0°C to 500°C; optional: 2,000°C	0.08°C at 30°C	FPA, uncooled microbolometer	320×240	50–60 Hz	Salas-Bringas et al. (2007)
Thermovision 550	AGEMA Infrared	3.6–5	−20°C to 250°C;	0.1°C at 30°C	FPA, uncooled	320×240	50–	Berry (2000)

Table 1 (continued)

Camera model	Manufacturer	Spectral range, µm	Temperature range	Thermal sensitivity	Detector type	Image size	Frame rate	References
	Systems, New Jersey, USA		1,500°C (with filter)		microbolometer		60 Hz	
VARIOSCAN 2011	Jenoptic Laser, Jena, Germany	10	−40°C to 1,200°C	0.1 K at 30°C	HgCdTe, liquid nitrogen cooled	NA	NA	Hellebrand et al. (2000)
VARIOSCAN 3021 ST	Jenoptic Laser, Jena, Germany	8-12	−40C to 1,200°C	0.03 K at 30°C	HgCdTe, stirling cooled	360×240	NA	Oerke et al. (2006)
VIGOcam v50	Vigo Systems, Warsaw, Poland	8–14	−10°C to 100°C or 0 to 350°C, optional: 1,500°C	0.08°C at 30°C	FPAUncooled microbolometer	384×288	30–60 Hz	Baranowski et al. (2009)

InSb indium antimonide, *HgCdTe* mercury cadmium telluride, *NA* not available

Crop Water Stress

Use of thermography for monitoring canopy temperature, identifying plant stress, and estimating stomatal conductance to aid in irrigation scheduling were studied by many researchers (Jones et al. 2002; Jones 1999a; Jones 1999b; Leinonen & Jones 2004). Leaf water potential (LWP) is a widely accepted parameter for monitoring water status and irrigation scheduling for plants. Sela et al. (2007) used thermal and visible images to generate leaf water potential status of cotton crops (*Gossypium barbadense* L.). Thermal images were obtained using a ThermaCAM SC2000, thermal camera and digital RGB images were acquired using a digital camera (DSC-F717, Sony Inc., Tokyo, Japan) attached to the thermal camera. All measurements were conducted mainly during flowering and boll development stages during which most water is applied to the plants. Crop water stress index (CWSI) was calculated based on canopy temperatures and theoretical and empirical references. LWP was measured from models built by CWSI and the models based on empirical references showed good correlation with measured LWP. They concluded that LWP maps can help in irrigation scheduling and can provide support to determine the defects in irrigation system.

Stoll and Jones (2007) explored the possibility of using thermal imaging as a tool for monitoring plant stress. The experiments were conducted on mature grapevines (*Vitis vinifera*) growing on deep sandy soil and the treatments were no irrigation and full irrigation and images were obtained using IR Snapshot 525 thermal camera. The temperature of Moscatel variety with sunlight for irrigated and non-irrigated conditions were 35.1 and 36.5 °C, whereas the temperature of the Moscatel in shaded area for irrigated and non-irrigated conditions were 32.6 and 33.5 °C, respectively. Their study showed that temperature difference between stressed and non-stressed plants could be very helpful to identify water stress in plants and this could be used in irrigation scheduling.

Monitoring stomatal conductance can be a better indicator of plant response to drying soil than monitoring water potential because reductions in stomatal conductance can occur even before any change in plant water status (Jones 2004). Thermography seems to have a great potential because as water is lost through stomata, leaves cool and hence as stomata close, leaf temperature rises which could be detected through thermal imaging. Grant et al. (2006) conducted studies aimed at comparing the precision of thermography and conventional porometry and water relation measurements between water stressed and well-watered control plants under greenhouse conditions using IR Snapshot 525 thermal camera. The experiments were conducted with grapevines (*V. vinifera* L), French beans (*Phaseolus vulgaris* L.), and lupins (*Lupinus*

Table 2 Applications of thermal imaging in agriculture

Crop	Problem	Results from IR thermal imaging studies	References
Cotton (*Gossypium barbadense* L.), grapevines (*Vitis vinifera* L.), French beans (*Phaseolus vulgaris* L), lupins (*Lupinus albus* L)	An easy method to monitor plant stress, stomatal conductance, and canopy temperature is not available	Water stress in plants, and canopy temperature could be identified using thermal imaging, which could be used in scheduling irrigation	Stoll and Jones (2007); Sela et al. (2007); Jones 2004; Grant & Chaves 2005
Tobacco (*Nicotiana tabacum* L), grapevines (*Vitis vinifera* L.), cucumber (*Cucumis sativus* L.)	Difficult to identify plants affected by diseases and pathogen	Pathogen- and disease-infected sites were detectable even before the initial appearance of lesions	Chaerle et al. (1999); Stoll et al. (2008); Oerke et al. (2006)
Potato (*Solanum tuberosum*), cauliflower (*Brassica oleracea*), barley (*Hordeum vulgare*)	Existing methods to determine ice nucleation and freezing behavior of plants are unreliable	Thermal imaging could explain where ice nucleates and how it spreads in plants and the order in which freezing occurs	Fuller and Wisniewski (1998); Pearce and Fuller (2001)
Citrus (*Citrus sinensis*), apple (*Malus domestica*)	Hand harvesting is expensive; to develop robotic harvesting, fruit recognition is a challenge	Aids in developing robotic fruit harvesting; possible to predict the yield of fruits in an orchard	Bulanon et al. (2008); Stajnko et al. (2004)

albus L.). Stomatal conductance and leaf temperatures were measured on the same leaves, with porometer measurements immediately following thermal imaging. Based on the results, they concluded that a good correlation was found between the I_G index $((T_{\mathrm{dry}}-T_{\mathrm{leaf}})/(T_{\mathrm{leaf}}-T_{\mathrm{wet}}))$ obtained from thermography and stomatal conductance measured with a porometer. However, they recommended few guidelines to optimize the technique: the time between spraying the wet reference leaf and taking image must be standardized, all plants and reference must be subjected to the same amount of radiation environment and the imager must be allowed to equilibrate before measurements.

Grant and Chaves (2005) studied thermal imaging for identifying water stress in grapevines of cultivar Aragonez with three irrigation treatments (deficit irrigation, regulated deficit irrigation, and partial root zone drying) using a IR Snapshot 525 thermal camera. Their results suggested that canopy temperature was more useful for detecting water stress than leaf temperature because canopy temperatures are based on average temperature over a group of leaves. When images were taken for individual leaves, temperature and index values obtained were not correlated with stomatal conductance because leaves at similar temperature may have different stomatal conductance based on orientation and inclination angles of leaves.

Merlot et al. (2002) studied the use of infrared thermal imaging to isolate *Arabidopsis* mutants defective in stomatal regulation using ThermaCam PM250 thermal camera. Plants synthesize abscisic acid (ABA) hormone which triggers the closure of stomatal pores during periods of drought to conserve water by reducing transpirational water loss. Leaf temperature can be used as an indicator to detect mutants with altered stomatal control. They used ABA-deficient and ABA-insensitive mutants as controls to optimize experimental conditions for thermographic detection of individual plants with altered stomatal response. These conditions were then used to perform pilot test for mutants that displayed a reduced ability for stomatal closure. They identified mutations at two novel loci that inhibit ABA regulation of stomatal aperture.

Pathogen Detection

Stoll et al. (2008) explored the potential of thermal imaging for pathogen detection in grapevine (*V. vinifera* L.) under different water status. Experiments were conducted under greenhouse conditions to monitor leaf temperature of *Plasmopara viticola* pathogen-infected and non-infected areas under different irrigation treatments: (1) control, irrigated to field capacity and non-inoculated vines; (2) irrigated to field capacity and inoculated vines; (3) non-irrigated and non-inoculated vines; and (4) non-irrigated and inoculated vines. Thermal images were obtained using a TH7102MX thermal camera. The analysis of thermal images showed that pathogen development caused an increase in leaf temperature at the point of infection in irrigated vines and the plants under severe water stress (non-irrigated) showed a lower temperature at the sites of inoculation. The authors could not state the mechanism causing the contrast effect on leaf temperature due to difference in water status of the plant but the study showed that thermal imaging could be used as an indicator for early detection of stress and providing information on the interaction of biotic and abiotic stressors.

Downy mildew of cucumber (*Cucumis sativus* L.) leaves is caused by the pathogen *Pseudoperonospora cubensis*, which results in changes in metabolic processes including transpiration rate. Oerke et al. (2006) explored the potential of thermal imaging to determine the effect of downy mildew on cucumber leaves. Cucumber seeds were germinated on moist paper, transplanted to plastic pots, and grown in greenhouse at 20–25 °C and 70+10% RH. About 5 ml of *P. cubensis* suspension was sprayed on the leaves using hand sprayer and the plants were assessed daily for mildew development. Thermal images were obtained using VARIOSCAN 3021 ST thermal camera. The maximum temperature difference between healthy and infected leaves was studied using thermal images recorded day by day up to 8 days after inoculation. Two days after inoculation with *P. cubensis*, the temperature of affected leaves was 2 °C higher. The maximum temperature difference within the infected leaves was significantly larger than the maximum temperature difference of non-inoculated plants.

Hellebrand et al. (2006) studied the possibility of detecting infested plants using thermal and NIR imaging under laboratory and field conditions. Wheat (*Triticum aestivum*, variety "Kanzler") plants artificially infected by powdery mildew (*Blumeria graminis*) were thermally imaged using ThermaCAM SC 500 or ThermaCAM 545 and NIR images were obtained using ALPHA NIR^{TM} (Indigo Systems Corporation). Their results showed that temperature of the infested plants was lower compared to healthy plants in the range of 0.2 to 0.7 °C and hence infested plants could be identified using thermal imaging under the laboratory conditions. Whereas under field conditions, temperature variability of soil and plants superposed temperature changes due to infestation and hence hampered the detection of infested plants. They concluded that NIR imaging as a standalone method was not suitable for determination of infested plants while thermal imaging was useful under laboratory conditions.

Chaerle et al. (1999) studied the presymptomatic determination of plant virus interaction by use of thermal camera THV 900 LW. Salicyclic acid (SA) produced by plants as a defense signal against pathogens induces metabolic heating, and when exogenously applied, increases leaf temperature. The authors applied SA to tobacco leaves and determined the resistance of tobacco mosaic virus before any disease symptom was visible on tobacco leaves. When SA was applied to tobacco leaves, the infected sites were 0.3–0.4 °C warmer than the surrounding tissue and were detectable 8±1 h before the initial appearance of necrotic lesions.

Ice Nucleation

The detection of ice formation in plant tissues is challenging and the electronic recording of plant temperature using thermocouples and examining the latent heat of crystallization of water at the point of freezing was the only method available until recently. This method is difficult and unreliable because many thermocouples need to be attached and these inserted thermocouples may damage cells leading to ice nucleation at that site and sometimes even carefully attached thermocouples may become detached during testing. Fuller and Wisniewski (1998) used infrared thermal camera Inframetrics Model 760 LW to study ice nucleation and freezing behavior of potatoes (*Solanum tuberosum*) and cauliflower (*Brassica oleracea*). Thermal imaging of potato plants showed that during freezing, leaves rapidly equilibrated (within seconds) to the temperature of the air while the stems cooled more slowly (5–10 min). The thermal imaging of cauliflower head showed that the coldest zones were those that were most peripheral, i.e., the tip of the floret while the warmest zones were the cracks and crevices between florets. The use of thermal imaging gave insight into where ice nucleates and how it spreads in two plant species. For potato plants, supercooling to sub zero temperature (−6 to −8 °C) was possible without any physiological damage; however, once these plants froze, then shoot death was complete within 10 min of nucleation. Their work was the first published visualization of ice nucleation and demonstrates that infrared imaging can be used to investigate frost hardiness in plants.

Pearce and Fuller (2001) studied the freezing of barley (*Hordeum vulgare* cv. Gleam) by infrared video thermography using Inframetrics thermal camera Model 760 LW. Their results showed that organs of barley froze in this order: nucleated leaf, roots, older leafs, younger leaves, and secondary tiller. Initial spread of freezing was not damaging but the ice formed during first freezing event initiates second freezing event, which causes the damage.

Determination of Fruit Yield

Bulanon et al. (2008) studied the temporal variation in citrus (*Citrus sinensis*) canopy for citrus fruit detection using thermal imaging. The focus of the study was on fruit recognition from the canopy, to enhance the robotic harvesting of fruit, which is an alternate for harvesting by hand. The thermal camera ThermaCam P65HS was positioned 2 m from the region of interest on the canopy surface and images were acquired for 24 h at 15 min interval. The images were analyzed using Matlab and the fruit and leaf temperature had the same trend throughout the region of interest. From evening 16:00 until early morning, the fruit temperature was higher than the leaf by about 1.6 °C while in the other time range, the temperature was higher only at less than 0.6 °C. Their results suggested that thermal imaging has a potential to distinguish between fruit and canopy from afternoon until midnight.

Stajnko et al. (2004) demonstrated the applicability of thermal imaging for predicting the number and diameter of apple (*Malus domestica*) fruits to calculate the yield in an apple orchard. Thermal camera AGEMA 570 was used for the experiment and images were captured at five stages of fruit development and images were recorded late in the afternoon to achieve temperature gradient between fruits and the background. Various image processing algorithms, thresholding, filtering, and longest segment algorithms were used to differentiate the fruits from the background and the leaves. The results of the study showed that a close correlation (R^2=0.83–0.88) existed between manually counted fruits and fruits determined by thermal imaging. The correlation coefficient was R^2=0.68 to 0.70 between manually measured diameter and the diameter of fruit determined by imaging.

Post-harvest Operations: Quality Evaluation of Agricultural Products

Thermal imaging has potential applications in many post-harvest operation such as quality evaluation of fruits and vegetables, quality testing of meat, detection of foreign materials in food, temperature mapping in cooked food and grain, drying, and detection of defects in packaging. Table 3 describes the applications of thermal imaging in post-harvest and quality evaluation operations. In Table 4, the applications of thermal imaging are listed with the temperature difference determined in various research studies.

Bruise Detection in Fruits

Bruising is the major factor for rejecting fruits during sorting because bruised fruits can cause significant damage to unbruised fruits during storage as well as consumers are not willing to purchase fruits with bruises. The existing sorting systems are not capable of effectively distinguishing fruit with bruises which has occurred a short time before inspection. Baranowski et al. (2009) developed a method to detect early bruising in apple using pulsed-phase thermography (PPT). Apple (*M. domestica* Borkh) varieties, Jonagold, Champion and Gloster were subjected to bruising by a specific procedure and stored at room temperature for 1 h before thermographic bruise assessment. The experimental set-up consisted of VIGOcam v50 thermal camera with two halogen lamps and a system for controlling the heat pulse time. In the first stage of study (no heat stimulation), the temperature difference between sound and bruised areas as well as between shallow and deeper bruises were close to 0°C, indicating that passive thermography could not be used for early bruise detection. Whereas, after heating the apple for 1 s, considerable temperature difference between bruised and sound apples were seen. The temperature of the bruised part was colder and variation ranged between 0.9 and 1.5°C for Jonagold, 0.9 and 1.8°C for Champion, and 1.0 and 2.1°C for Gloster apples. They concluded that with the use of PPT, it was possible to distinguish bruised apples at the early stages and the bruises reaching various depths under the skin of the apple.

Varith et al. (2003) explored the potential of using thermal imaging to detect bruises in apples by sensing thermal diffusivity (α) differences between bruised and sound tissue because rate of heating or cooling is different for damaged and sound tissues. Apples (Fuji and McIntosh) were dropped from 0.46 m onto a smooth concrete floor and held at 26°C and 50% RH for 48 h to allow bruise development. Thermal images were taken using a ThermaCam^{TM} PM390 during heating and cooling treatments. The apples were refrigerated prior to imaging for at least 3 h and then randomly subjected to one of the three treatments: (1) heating with forced convection in ambient air; (2) heating with forced convection in the air heated to 37°C; and (3) cooling with forced convection after being heated in 40°C water for 2–3 min. The results showed that heating treatments 1 and 2 were more successful in bruise detection than the cooling treatment and the temperature of bruised tissue lagged up to 1–2°C behind the sound tissue temperature. The bruise detection was due to thermal diffusivity differences between the damaged and sound tissues and not due to the thermal emissivity differences, because there was no temperature difference between bruised and sound tissue at thermal equilibrium. They concluded that first treatment gave 100% accuracy for bruise detection within 180 s or less, second treatment gave slightly less accurate results but in 90 s and the cooling treatment gave 66% accuracy in 90 s in bruise detection in apples.

Veraverbeke et al. (2003) evaluated the surface quality of two different apple cultivars (Elshof and Jonagored). Temperatures were recorded during cooling of individual fruits from 20 to 12°C and storage experiment was carried out under standardized conditions and quality assessment of apples after 4 and 8 months of control atmosphere storage was done. Their results showed a difference in cooling rate between the two cultivars, which was related to the differences in wax structure between the two and Elshof had a faster cooling rate and lower temperature than Jonagored.

Danno et al. (1977) demonstrated the potential of grading of fruits for bruise and other surface defects by infrared imaging using Infra-Eye 102A thermal camera. Apples and mandarins were selected for the study and the fruits were artificially damaged by pressing and scratching. The fruits were kept at constant temperature for 24 h before measurement and the constant temperature was higher (30°C) or lower (10°C) than the room temperature. The thermal images of bruised and unbruised fruits showed a difference in the temperature range of 0.2–1.0°C and the temperature of the bruised fruits were lower than the unbruised fruits.

Table 3 Applications of thermal imaging in post-harvest and food industry operations

Product	Problem	Results from IR thermal imaging studies	References
Apple (*Malus domestica*)	Bruise detection in fruits is a major issue in fruit quality	Possible to determine bruises at an early stage	Baranowski et al. (2009); Varith et al. (2003); Danno et al. (1977)
Apple, cherry tomato (*Solanum lycopersicum*) Japanese persimmon (*Disopyros kaki* L), Japanese pear (*Pyrus serotina* Rehder), tomato (*Lycopersicon esculentum* Mill)	Non-destructive method for maturity evaluation is not available	IR thermal imaging makes it possible to determine the maturity of fruits	Hellebrand et al. (2000); Offerman et al. (1998); Danno et al. (1980)
Wheat (*Triticum aestivum*)	Lack of rapid online method to determine varietal purity	IR imaging has a potential to identify wheat classes	Manickavasagan et al. (2008a; 2008b)
Hazel nuts, chocolate chunks	Lack of system to determine all contamination in food irrespective of shape or size	Possible to determine all sorts of impurities such as leaves, stalks, pedicels, thorns, and foul nuts	Warmann and Märgner (2005); Ginesu et al. (2004)
Potato (*Solanum tuberosum*)	Maintaining optimum temperature in a storage facility is a challenge	Optimization of climate control in storage facility is feasible	Geyer et al. (2004)
Wheat (*T. aestivum*)	Rapid detection of insect infestation is a challenge	Insect infestation could be determined to certain accuracy in wheat using IR thermal imaging	Manickavasagan et al. (2007)
Ground beef; grain	Temperature mapping not feasible	Temperature mapping enables safe cooking temperature and safe temperature to maintain seed quality	Berry (2000); Manickavasagan et al. (2006)
Citrus (*Citrus sinensis*)	Citrus surface drying results in reduced sensory quality and shelf life	Drying time could be established; fruit quality could be improved	Fito et al. (2004)
Packaging material	Non-destructive technique to detect packaging defect not available	IR imaging has potential to detect cracks, delamination, and voids in packaging material	Liu and Dias (2002)

Maturity Evaluation of Fruits

Firmness and maturity are important attributes regarding the quality of fruits and vegetables. These parameters are determined by visual inspection, ultrasound or destructively using a pressure tester. There is a search for an alternative non-destructive method for maturity evaluation of fruits and vegetables.

Hellebrand et al. (2000) evaluated the use of thermography for determination of mechanical damage, bruising, and maturing of apples (Jonagold, Cox) using VARIOSCAN 2011 thermal camera. Their results suggested that

Table 4 Applications of thermal imaging and the corresponding temperature ranges in various applications

Application	Temperature difference	References
Irrigation scheduling	0.9–3.8°C	Stoll and Jones (2007); Sela et al. (2007)
Maturity evaluation of fruits	0.5°C	Danno et al. (1980); Offerman et al. (1998); Hellebrand et al. (2000)
Bruise detection	0.9–1.8°C and 0.2–1.0°C	Danno et al. (1977); Varith et al. (2003); Veraverbeke et al. (2003); Baranowski et al. (2009)
Estimating crop yield	0.6–1.6°C	Bulanon et al. (2008); Stajnko et al. (2004)
Pathogen detection	2°C	Stoll et al. (2008); Oerke et al. (2006)
Storage of potato	1.5–9°C	Geyer et al. (2004)
Plant virus interaction	0.3–0.4°C	Chaerle et al. (1999)
Fungal disease detection in plants	0.2–0.7°C	Hellebrand et al. (2006)
To determine package defects	0.2–0.3°C	Liu and Dias (2002)

mechanical damages can be detected by means of localized temperature decrease. Because bruising of apples causes cell defects without damaging the skin and the changes in temperature were lower than 0.1 °C, therefore, bruising was not measurable by thermal imaging. They also suggested that maturity of apples can be estimated by thermal imaging and different varieties of apples could be identified if they are of the same ripeness.

Offermann et al. (1998) explored the potential of non-contact, non-destructive, infrared thermography to detect apples (*M. domestica*; green Granny Smith and red and yellow Elstar) and cherry tomatoes (*Solanum lycopersicum*; red, orange-red, green-yellow, and green) at different maturity stages. The samples were placed on a 1 m distant platform and energized by a short and intense pulse of light for 5 ms from four lamps (3,000 J). No damage was done to the samples due to the incident energy and the resulting temperature decay rate was measured using AGEMA 880 LW thermal camera. The results of cherry tomatoes showed that red and orange tomatoes are more effectively heated than the green ones, indicating higher absorption of light in the skin of red and orange tomatoes. For the apples, the Elstar yellow was more transparent to the flash radiation than the red Elstar or green Granny Smith apples. The results of the pulsed infrared thermography study indicated that to some extent the products can be distinguished by the skin temperature. However, due to combined effect of optical (semi-transparency and light scattering within apples) and thermal (heat diffusion) phenomena, interpretation of data remains a difficult task.

Danno et al. (1980) studied the potential of maturity evaluation of three different fruits: Japanese persimmon (*Disopyros kaki* L), Japanese pear (*Pyrus serotina* Rehder), and tomato (*Lycopersicon esculentum* Mill) using Infra-Eye 102A thermal camera. The maturity grades were divided into three: immature, mature, and over-ripe fruits based on color, firmness, and sugar content. Their experiments showed that the surface temperature of immatured fruits and vegetables, stored at lower temperature was slightly higher than matured and over-riped ones. The surface temperature of immature fruits and vegetable stored at higher temperature was slightly lower than those of matured and over-riped ones.

Quality of Ham

Nanni Costa et al. (2007) used thermography for the assessment of pork and ham suitability to be processed as dry cured ham on the slaughter line. Thermal images were obtained on left and right ham of 40 carcasses of pigs using ThermaCam P25 thermal camera. Their results showed no difference in the average temperature among the various parameters such as pH, color values, and ham defects such as veining or red skin. But hams with lower fat cover showed a significantly warmer surface temperature and it was suggested that lower thermal insulation due to a thinner subcutaneous adipose tissue might be responsible for higher skin temperature. They concluded that infrared thermography could be a fast and non-invasive method to estimate the fat content of ham.

Detection of Foreign Bodies in Food

The presence of foreign bodies in food is a major safety concern and various methods are employed in the food industry. Visual inspection is commonly used but it is affected by several factors. Physical separation methods such as sieving, sedimentation, screening, filtering, and gravity systems are used and more sophisticated systems such as metal detectors, X-ray machines, optical sensors, and ultrasonic methods are used for the detection of foreign objects. But there is no system capable of determining every contaminant regardless of size and shape.

Warmann and Märgner (2005) studied the detection of foreign bodies in hazelnuts and thermal image analysis of single nuts to inspect the quality of individual nuts using a Thermosensorik CMT 384 thermal camera. The hazel nuts along with foreign bodies were made to pass on a conveyor belt and slightly heated. After a fixed period of cooling time, thermal images were captured. They used image processing techniques such as thresholding and texture analysis algorithms. The study implies that thermal imaging could be used to detect foreign materials and determine the quality of individual hazel nuts such as the ones with insect stings or foul nuts. Since their study was tested under laboratory conditions, the authors suggested that extensive test under industrial condition need to be performed.

Ginesu et al. (2004) studied the potential of thermal imaging to detect foreign bodies in food products using a Thermosensorik CMT 384 thermal camera. To distinguish between a food material and a foreign body, either the emissivity or the different heat conductive capacities of the material should be used. Since difference in emissivities may not produce good contrast images, they used the difference in heat capacities of food and other materials to detect undesirable materials. The food materials chosen were almonds and raisin and foreign bodies were wooden stick, stone, metal chip, and cardboard. They used a pulse thermography and the experimental procedure was that the object was placed (food material and foreign body) on a conveyor belt under the camera and a heat pulse was applied; and then the decrease in surface temperature was observed. Due to difference in heating capacities, different object will cool down with different speed and they recorded a long sequence (500 frames, 80 frames per second) and extracted the thermal images. They applied various image processing techniques such as binarization, statistical, and morphological analysis. They concluded that results are promising and thermal imaging has a potential to detect foreign bodies in food materials.

Meinlschmidt and Märgner (2002) conducted two different studies to detect foreign substances in food using Thermosensorik CMT 384 thermal camera. The first one was to detect the presence of cherries in chocolate chunks by their emissivity coefficient without applying any heat impact. The second study was to detect the presence of leaves, stalks, pedicels, and thorns in a variety of different fruits by difference in the heat conductivity or capacity of different materials by allowing the materials to pass on the conveyor belt with a heat source and a thermal camera captures the image during the state of decreasing temperature (Fig. 2). Their results showed that thermography could be used to detect foreign substances in the food material but they suggested that these methods have to be tested on a larger scale material in real-time environment.

Storage

To maintain an optimum temperature of 5°C in potato storage facility is a challenge and thermal imaging offers a possibility to visualize processes like warming-up, cooling, and air flow development in the storage facility. The potential of using thermal imaging to optimize the climate control of potato storage was demonstrated by Geyer et al. (2004). An infrared thermal camera ThermaCam SC 500 was used for the experiments. The results of experiments supplied valuable information about temperature distribution in a big box potato store. There was a wide temperature range between the front and the sides of the wooden boxes ranging from 1.5 to 9°C and wide temperature variation also occurred between the stacks of potatoes in the wooden box. Hence, thermography provided a good view of the temperature differences within a potato storage facility which could be used for designing a temperature control system to provide uniform temperature within the storage.

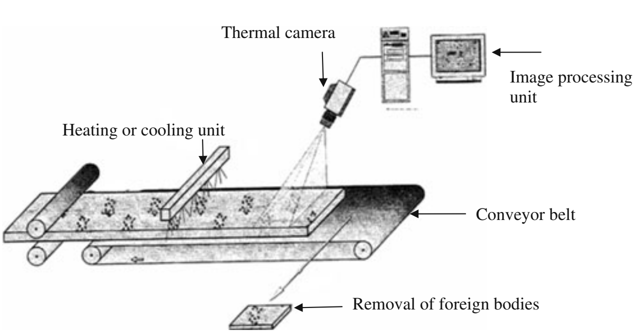


Fig. 2 Experimental set-up for detecting foreign bodies in a food stream (source: Meinlschmidt & Märgner 2002)

Grain Storage

In Canadian grain handling facilities, Berlese funnel is the most commonly used method to detect insect infestation (Canadian Grain Commission 2004). It is a time-consuming method and the accuracy is low for developing life stages. The thermal imaging could serve as an alternative method to detect insect infestation because, the respiration of insects result in heat production higher than that of the grain (Damcevski et al. 1998; Emekci et al. 2002). An infrared thermal camera ThermaCAM SC500 was used by Manickavasagan et al. (2007) to test whether insect infestation could be determined using thermal imaging. The Canada Western Red Spring (CWRS) wheat kernels were artificially infested with eggs of *Cryptolestes ferrugineus* (Stephens) (Rusty grain beetle) and thermal images were acquired on days4, 8, 11, 15, 22, and 27 to represent four larval stages, pupal, and adult stages, respectively. The classification accuracy for quadratic function was 83.5% and 77.7%, for infested and sound kernels, respectively, and in linear analysis, classification accuracy was 77.6% and 83.0%, respectively, for infested and sound kernels. They concluded that insect infestation could be determined by thermal imaging to certain accuracy, but it is less effective in identifying the developmental stages of the insect.

In grain handling facilities, most of the grading factors including varietal purity are determined by visual inspection which is a subjective method and leads to error in many circumstances (Majumdar & Jayas 2000). Manickavasagan et al. (2008a, b) explored the possibility of thermal imaging as a rapid online method for identifying various wheat (*T. aestivum*) classes. Eight major wheat classes in Canada: Canada Prairie Spring Red, Canada Prairie Spring White, Canada Western Extra Strong, Canada Western Hard White Spring, Canada Western Red Spring, Canada Western Amber Durum, Canada Western Red Winter, and Canada Western Soft White Spring were used for the study and thermal images were obtained using ThermaCAM SC500 camera. Three images were taken for each sample: before heating, after heating for 180 s, and after cooling for 30 s. The results of the study showed that classification accuracy was in the range of 57–88% for the eight-class model and the classification accuracy improved between 76–95% for four-class model (red and white class wheat classified separately). They concluded that although thermal imaging has a potential to identify wheat classes, further investigations to study the performance of the system with composite samples is necessary.

Thermal Imaging in Processing

Temperature is the most frequently measured variable in any process engineering but its assessment is always not accurate (Berrie 2001). During pelleting, temperature is a critical parameter and high temperature in a moist food or feed material results in a wide range of physical and chemical changes. Salas-Bringas et al. (2007) studied the non-contact temperature monitoring of a pelleting process of poultry feed using infrared thermography and Thermo-Vision A40M thermal camera was used. The experiment was carried out in a Pellet Press (Münch Edelstahl, Germany) with two corrugated rollers and assembled with a double conditioner. The infrared camera was installed and temperature monitored at various locations such as: pellets at the die exit and surface of rotating die/pellets, temperature of meal at the outlet of the conditioner, and pellets at the outlet of the pellet press. The experiment showed that temperature increase in the meal was not only because of the friction in the die hole, but also because of the stress, strain, and friction produced in the gap between the rollers and die ring, and the heat transfer from the hotter die. They concluded that IR thermography facilitates temperature measurement of sticky material, moving objects and temperature distribution within the products in a process. They also suggested that improved instrument design was required for operation in dusty, damp, steamy, and oily environments.

Escherichia coli Detection

Traditional methods for isolation and identification of *E. coli* from contaminated food are time consuming and labor intensive (Catarame et al. 2003). Since *E. coli* respiration generates a small but significant amount of heat that can be detected by thermal camera, Hahn et al. (2006) explored the possibility of determining *E. coli* at their earlier stage using thermal imaging. An infrared thermal camera Model D500 was used to image sterile agar and those inoculated with culture of *E. coli*. Detection accuracies ranged between 75% and 100% and hence they concluded that *E. coli* could be detected using thermal imaging and the minimum time required for detecting microbial contamination was 5 h. They suggested that *E. coli* should be applied to vegetable and meat surface to determine whether they can be detected at the same rate in the food materials.

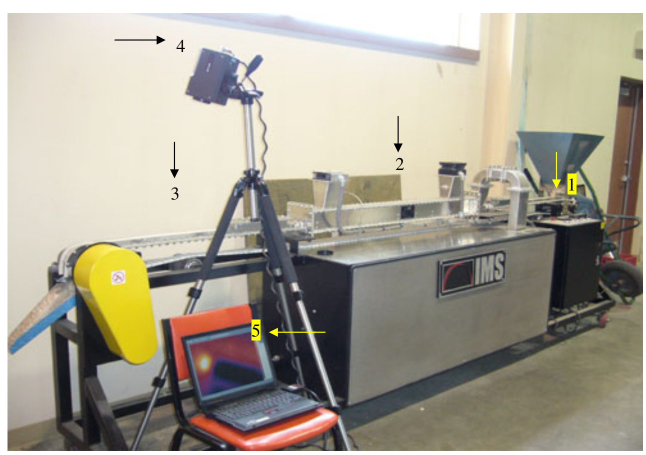
Temperature Mapping in Food and Grain

Inadequate cooking of ground beef may result in food-borne illness attributable to *E. coli* O157:H7, hence it was suggested to cook the ground beef patties to at least 71 °C (USDA 1998). Berry (2000) assessed the temperature variability in beef patties cooked from frozen versus thawed state using infrared thermography. Cooked beef patties were cut perpendicular to the flat surface within 5 s from the removal from the electric griddles and infrared images were captured within a second of making the cut using Agema Thermovision 550 thermal Camera. The observed temperatures were in the range of 54.4 to 73.9 °C. These are not actual temperatures but slightly lower due to rapid evaporative cooling of patty surfaces. Infrared imaging showed that internal temperatures were higher and more consistent for patties cooked from thawed state than for frozen patties.

The non-uniformity of surface temperatures of grain after heating in an industrial microwave dryer (2,450 MHz) was determined using thermal imaging (Fig. 3) by Manickavasagan et al. (2006). An infrared camera ThermaCAM SC500 was used to determine the surface temperature distribution in barley, wheat, and canola. The average surface temperatures after microwave treatment were between 72.5 to 117.5 °C, 65.9 to 97.5 °C, and 73.4 to 108.8 °C for barley, canola, and wheat, respectively. Hence, infrared thermal imaging could be used to determine the surface temperature mapping of grain which is important in predicting the end use quality of grain.

Drying

Surface drying is an important unit operation in a fresh fruit processing plant. In a citrus surface drier, using an excessive air temperature or drying the fruit for long-time results in loss of sensory quality and reduced shelf life of the fruit. Fito et al. (2004) tested a system to control the surface drying time of citrus using infrared imaging. An AGEMA Thermovision 470 camera was installed on the dryer to record the infrared emission from the surface of the oranges, var. *Valencia Late (C. sinensis)*. Their experiment showed occurrence of two drying steps: the lowest temperature value at the beginning of drying process was considered as the true wet bulb temperature and the end of



1. Control panel 2. Microwave applicator 3. Conveyor 4. Thermal camera
5. Data acquisition system

Fig. 3 Industrial microwave system with a thermal camera first drying step occurred when the entire orange surface was at a higher temperature than the wet bulb temperature. The next step was the orange peel drying which occurred when no water was present on the orange surface and it must be avoided because it contributes to the fruit surface damage. Drying time could be established using IR thermal cameras and an empirical model was developed to correlate drying times with air conditions. Their study revealed that image analysis using infrared thermal camera could be used as a non-destructive measure to determine final drying time and hence can improve the fruit quality.

The properties of a dried surface can be controlled by the manner in which a solvent evaporates from the surface. Infrared thermography can detect the point at which surface drying begins because evaporative cooling is lost at this point and the surface temperature rises. Fike et al. (2004) studied the drying of surface by infrared thermography using AGEMA 900SW/TE thermal camera. The authors demonstrated the technique with two applications: wood drying where the surface is rough, and the deposition of an organic film from water on a smooth metal surface. Since the temperature rise is initially very small and difficult to detect, the coefficient of variance of the temperature can detect the onset of surface dryout with greater sensitivity. They concluded that coefficient of variance analysis of infrared thermography provides a method for visualizing the breakage of a liquid film on metal surface or the onset of wooden surface drying. This technique could be used in the design and monitoring of process where film dewetting is important.

Packaging

One of the key challenges in the packaging industry is to develop a non-destructive technique to detect package defects such as cracking, delamination, and voids. Liu and Dias (2002) studied the potential of thermal imaging to identify packaging defects. The principle is that when heat is applied to an object, it diffuses from the source to the surrounding material. Any flaw in the material affects the diffusion rate which in turn affects the temperature in the vicinity of flaw and as a result, changes the temperature profile on the surface of the material, which could be detected by surface thermal response of infrared imaging. In this study, a thin layer of thermal interface material (TIM) was sandwiched between silicon die and lid and the four samples with different TIM defect were tested: without TIM defect, TIM delamination, lack of TIM, and no TIM. The testing system consists of a heating source, IR camera (3–5 μm) with indium antimonide detector, data acquisition, and image processing system. Their results showed a temperature difference of 0.2–0.3 °C between the normal surface and surface with defects. They concluded that thermal imaging is a non-destructive potential tool for detecting packaging defects.

Conclusions

The thermal imaging technique plays a major role in temperature mapping of essential process and product in many industries and is gaining momentum in agriculture and food industry. Some of the applications are already being used while some are still under research phase and most of them seem to have a great potential to be used in real time situation in the near future. In agriculture, thermal imaging has wide application in determining crop water stress, irrigation scheduling, pathogen and disease detection in plants, bruise detection and maturity evaluation of fruits, and yield estimation of fruits in the orchard. The non-contact, non-destructive, nature of thermal imaging along with rapid online usability are the major reasons for the fast growing demand for this technique in various fields. The researchers are exploring the potential of using thermal imaging in various processes in agriculture and food industry due to its numerous advantages.

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