International Journal of Current Agricultural Research Vol. 1, No.7, PP. 34-41 July 2013
http://www.wrpjournals.com/journals/V/IJCAR

Full Length Review Article

USE OF THERMAL IMAGING TO IMPROVE THE FOOD GRAINS QUALITY DURING STORAGE

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Accepted 09th June 2013; Published 26th July 2013

Thermal imaging is a technique which converts the invisible radiation emitted by an object into temperature data (visible image) without making contact with the object. This method is widely used for determination of surface temperatures, grain quality measurement like infested kernel, and presence of foreign bodies (dead insects, stones, rat excreta)in food produces. This paper reviews importance of thermal imaging in grain storage. The spoilage of grains occurs due to inadequate storage facilities, which leads to improper interactions between abiotic (temperature, moisture content, and gases composition) and biotic (grain itself, insects, fungi, moulds, and mites) factors. The grain storage losses can be reduced by understanding the stored grain ecosystem. This can be done by adopting loss detection and prevention techniques to increase the availability of grains for human consumption. Though the pre-treatments like cleaning and drying are necessary to obtain safe moisture content for better storage, the storage structure design and its construction plays a vital role in application of loss detection technology for reducing the losses during storage. Therefore, development of appropriate storage methodology for reducing grain losses has become a global challenge. Hence, an instantaneous study is required to understand interactions of these factors and manage them in appropriate manner to reduce the loss of grains both quantitatively and qualitatively. So application of thermal imaging would be an appropriate tool to protect the stored grains by detecting the hot spots by measuring grain temperature in storage bins.

Key words: Thermal imaging, grain storage, hot spots, infrared radiation, grain spoilage

INTRODUCTION

India produces a wide variety of food grains, like pulses, cereals, millets, and oilseeds, which are an important component of the vegetarian Indian diet. The total food grain production of India in 2011-12 was approximately 246.2 million tonnes of which the post-harvest losses accounted to about 10% of total production. The approximate value of about 20mT of grains wasted is nearly equivalent value to total annual food grain production of Australia (FAO, 2012). The post-harvest losses of food grain in India is in range of 7 to 10 % at farm to market level, and to an additional 4-5 % at the marketing and distribution level. Soon after the grains are harvested from the fields, various unit operations such as threshing, winnowing, bagging, transportation, storage, processing and distribution are carried out based on the requirements of consumers. The loss during each of the post-harvest unit operations accounts nearly 0.15% during transportation, processing (0.92%), threshing (1.68%), and highest during storage (6.58%). These are mainly caused due to lack of suitable handling and storage facilities for grains. The loss of food grains are also caused by environmental factors such as higher atmospheric temperature, pH, moisture, and relative humidity etc. (Sashidhar *et al.*, 1992).

Hence post-harvest losses of stored grains remain a problem in India and vigilant post-harvest grain management is the most cost-effective means of increasing the total food supply. It is estimated that 10-15% of the stored grain is lost every year due to insect damage in India (Sinha and Sinha, 1990). Some examples of the major insect pests of stored grain are *Rhyzoper thadominica* (lesser grain borer), *Oryzaephilus surinamensis* (saw toothed grain beetle), *Sitophilus oryzae* (rice weevil), *Trogoderma granaria* (khapra beetle), *Tribolium castaneum* (red flour beetle), and *Plodia interpunctella* (Indian meal moth). The loss of produced grain (qualitatively or quantitatively) will lead to far-reaching economic effects. Stored grain bulks are ecological systems, in which communities of insects, mites, and micro flora and a biotic variables cause spoilage due to their interaction with the grains (Wallace and Sinha, 1981). The contamination of grain by moulds is largely dependent on factors like temperature of the grain, oxygen and moisture availability and it is suggested that the rate of mould growth inside stored grain bulk increases with increase in temperature and moisture availability (Lacey, 1988). Moulds will utilize them moisture present in grain for its development and this moisture is expressed in terms of relative humidity of air. Hence the environmental factors such as temperature, relative humidity and gas composition greatly influence the rate of fungal spoilage due to fungal growth as well as the production of mycotoxins (Magan *et al.,* 2003). The survival and reproduction of biological agents in grain are dependent on the temperature and moisture levels inside grain kernel (White, 1995). Heat and moisture are produced when grain is spoiled by mould or insect attack, this heat in-turn cause temperature rise in grain thereby deteriorating its quality.

Hence, the storage life of grain depends mainly on two physical parameters like temperature and moisture content of grains (Jayas and White, 2003). Increased CO_2 levels indicate the presence of insects and mould which respires at higher rate inside grain bulk, thereby indicating the beginning of the grain deterioration. Therefore, carbon dioxide and odour volatiles produced from these biological pests increase during spoilage indicating the initiation of grain spoilage (Jayas, 1995; Magan and Evans, 2000; Maier *et al.,* 2006). Hence, the factors such as carbon dioxide, odour, temperature, moisture, and relative humidity are major indicators of bio-deterioration of grain in storage. The climatic conditions of tropical countries with high rainfall and humidity are ideal for the growth and development of micro-organisms and insects which cause high levels of deterioration of grains during storage. In order to reduce such losses, the environment in the storage needs to be controlled they will also help in lowering the possibility of biological damage by insects, rodents and micro-organisms, chemical damage due to rancidity

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development and flavour changes, etc. and physical damage due to crushing, breaking, etc.

Role of Moisture in Grain Quality

The moisture content of grains is an important factor in grain quality deterioration, as it limits the development of bacteria, fungi, mites and insects that cause spoilage of stored grains. While in general it is essential that all food grains are bought below their safe moisture content before they enter the storage room. The safe moisture content is some extent related to the required storage time, because lesser the moisture content of grain lesser will be the insect activity and respiration rate of grain. For majority of storage insect pests, moisture content below 10 % is not adequate for normal activity and development. Insect infestation tends to increase in moisture content above 10% up to a certain limit. Generally, insect activity is rapid at relative humidity exceeding 75%.One of the most remarkable features about the storage insect pests is that some of them can live in products having moisture content less than 10% (Sashidhar *et al.*, 1992). However, a certain minimum moisture level is needed and this varies considerably for different species. The minimum relative humidity as low as 60% would averts *Trogoderma granarium*, *Tribolium confusum*, *Tribolium castaneum*, *Callosobruchus analis*, *C. rhodesianus*, at this minimum level development is frequently very slow and mortality is high.

The moisture level above the safe moisture content can be tolerated if only for short storage periods as condensation of moisture will cause storage problems over longer periods of storage. It is also important to note that most stored food products are "alive" and respiring, thus generating moisture, as well as heat. If the walls of storage structures are cooled below their dew point, during night time due to lower temperature, condensation occurs and increases the moisture content in the layers of the grain adjacent to the walls. Meanwhile, having a relatively high moisture content the grain will respire at high rate, since the surrounding grain act as a thermal insulator, the heat generated in the respiration process will increase the grain temperature and this is added to the moisture already existing. This process may result in excessive temperature and excessive molding at affected area (Hukill, 1948). It has been established that most insects do not thrive below 9% moisture content of the grains. So, it is essential that before grains are put into storage, the moisture level should be 8% and absorption of the moisture from the air should be prevented.

Role of Temperature in Grain Quality

The temperature within a storage is affected by the external atmospheric conditions, the cooling effect of radiation from the grain storage, outside air temperature, heat generated due to respiration by the grains in storage bin as well as storage pest. Temperature is one of the most important extrinsic factor which exerts a profound impact on the rate of metabolism, growth, development, reproduction, general behavior and distribution of pests. The lower temperature at which the insects are able to develop lies between 15.5 and 18.3°C. The optimum temperature for most of the insects lies between 29.4 and 32.2°C (Paul, 1992). Most of the micro-organisms can thrive between 10 and 60°C temperature, whereas for insects the temperature ranges between 16 and 45°C. Normally, in tropics and sub-tropics, storage atmospheric temperature lies between 25 and 35°C which is favourable for the survival of the micro-organisms and insects. The metabolic heat produced exclusively by dry grain is about $1x10^{-7}$ calorie/s.cc (standard cubic centimetre) or$4.18x10^{-7}$ $J/cm^3$and wet grain is approximately $1.3x10^{-5}$ calorie/s.cc or 5.43 $x10^{-5}$ J/cm^3. The amount of heat produced by fungi and insects is much higher compared to the heat generated by grains (Sinha, 1973). Muir, 1997 indicated that, the heat production by respiration of any grain is around $0.01wt^{-1}$. Cofie-Agbloa *et al.* (1995b) showed that, the heat produced by an adult insect respiring for 10hours was around 66-81 μW of *Sitophilus granarius*, 46-56 μW of *S. oryzae,* 18-40 μW of *Tribolium castaneum* and 13-35 μW of *Rhyzopertha dominica*. Hence, when the grain temperature rises more than 20°C, grain getting infested with insects and microorganisms and at the same time its rate of respiration becomes rapid with the expense of chemical constituents. The grain temperature is always to be in conjunction with its moisture content. Grain temperature and grain moisture have intricate relationship which affects the food grains most under storage condition. Harrington's (1972) so-called Thumb rules states that life of seed is halved for each 5°C increase in storage temperature and for each 1% increase in seed moisture content with increasing temperature the speed of most enzymatic chemical reactions within the stored food grains increases till enzyme inactivation, which occurs at high temperature, resulting in retardation of chemical reactions (Kretovich, 1945).

The rise in temperature of grain bulk inside storage bin will leads to development of hot spots. This is because of differences in temperature between two areas or zones of the storage bin or silo. The hot spot is localized high temperature zones in a grain bulk. Hot spots may develop quickly in stored grain leading to deterioration of grains by accelerating many chain reactions. Depending on the origin, a hot spot may be classified into two types as a fungi-induced hot spot in damp grain or an insect-induced hot spot in dry grain (Sinha, 1967). Loading wet grain on top of the dry old grain, entry of rain through a roof leak, blowing of snow through ventilators, and rising of moisture through a cracked floor or moisture migration within the grain bulk may cause damp grain pockets in granaries. In a high moisture zone, moulds begin to grow and produce heat and moisture. *Penicillium* spp., *Aspergillus* spp., and *Absidia* spp. are commonly associated in fungi-induced hot spot (Wallace and Sinha, 1962). In an insect induced hot spot, moulds always grow in the hot spot area, producing more heat, moisture, and carbon dioxide. The generated heat and moisture stimulate the growth of the insects, moulds and respiration of grains, thereby leading to an accelerated chain reaction. The temperature difference between a hot spot and the surrounding cool grain in a grain bulk could be in the range of 10°C to 50°C (Sinha, 1961).

In literature it was reported that periodic inspection of storage once in a week is essential to monitor the temperature and moisture content of grain bulk in a storage bin at safe levels. In order to achieve this temperature and moisture content measuring system at various locations of stored grain bin is very mush essential. The general method of temperature measurement is generally performed by using large numbers of thermocouples, thermometers, thermistors, and resistant temperature detectors which are usually installed at various locations of bin. These instruments will measure the temperature only at specific points if the instruments are in contact with the object. In addition to this, measurements made are less accurate because these types of devices are affected by various environmental factors. Hence there is a necessity of non-contact and non-destructive temperature measurement method which is much more efficient than the conventional one. Therefore thermal imaging would be an appropriate tool for detecting the hot spots developed within the grain bulk due to variation in temperature between region to region. It also offers temperature measurement at various location of particular region captured as thermal image within a short period of time which is not possible in conventional method of measurement. Thermal images will provide a better view of temperature variations within the grain bulk which would be very helpful for monitoring temperature inside the storage bins.

Thermal Imaging

Thermal imaging is a technique where the infrared radiation emitted by any object is observed by infrared detectors and then these temperature data is converted into thermal image which shows temperature distribution within that particular region of captured image without making any contact with the object. It works on the principle that every object with its temperature above absolute zero (-273°C) emits heat radiation which are generally called as infrared radiation under the electromagnetic spectrum. The wavelength of these infrared radiations fall in the range of 0.78 µm to 1000 µm as shown in Figure1.These infrared radiations are further classified into different regions based on their wavelength like near infrared (0.75 - 3 µm), mid infrared (3-6 µm), far infrared (6-15 µm) and extreme far infrared (15-100 µm**)** (Meola and Carlo mango, 2004).The spectral range of infrared rays used, varies depending on the field of application. In most of the food industry application it ranges from 3-14 µm.

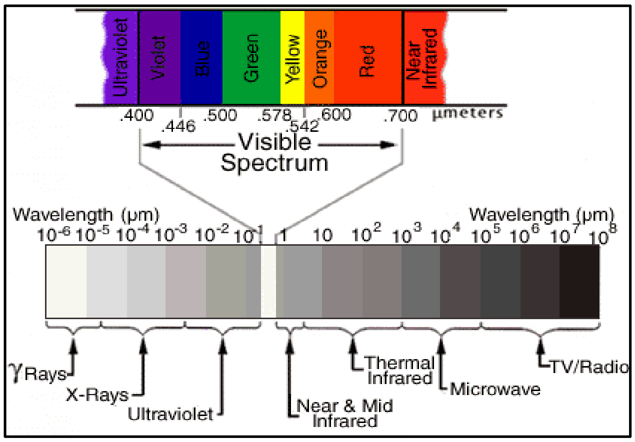

Fig.1: Electromagnetic Spectrum

(source: http://www.astro.virginia.edu/class/oconnell/astr121/121supps2-3.html, 2012*)*

The intensity of radiation emitted by the object mainly depends on surface temperature of that object, higher the temperature of the object greater will be the intensity of radiation emitted by the object. The intensity of radiation emitted mainly depends on the thermal properties of the object and these thermal properties effects the emissivity, absorptivity, transmissivity, and reflectivity of infrared radiation emitted by an object. It is revealed that the objects having good absorbing property will also have good emitting property and this relationship between absorptivity (α), reflectivity (ρ) and transmissivity (τ) of any object can be studied through Kirchhoff's law. The law states that when the object is at thermal equilibrium the sum of absorption, reflection, and transmission is equal to unity as given in the equation 1.

$$\propto + \rho + \tau = 1 \quad \text{------------------------ (1)}$$

It is also stated that, the total amount of radiation emitted by an object per unit area is directly proportional to the emissivity of that object and fourth power its temperature as shown in equation 2 (according to Stefan-Boltzmann law).

$$E = \sigma \varepsilon T^4 \quad \text{------------------------ (2)}$$

Where:

E = total emissive power of object per m^2 (Wm^{-2})
σ = Stefan-Boltzmann constant = 5.67 X 10^{-8} (Wm^{-2} k^{-4})
ε = emissivity of object
T = temperature of object (K)

Hence the temperature of the object can be calculated when the total radiation emitted and the object's emissivity values are known.

Thermal Imaging System

From the Figure 2 it is shown that the thermal imaging system mainly consists of three units, i.e., a thermal camera containing infrared radiation sensor (focusing lens with micorbolometers), a signal processing unit and an image processing unit (computer), each of these units have their unique function in the process of thermal imaging. When the infrared radiation emitted by object is incident on the infrared detectors of thermal camera these radiation will be converted into electrical signals and these signals are sent into the signal processing unit where it is translated and displayed as thermal image of temperature distribution over the object surface. In thermal imaging, a huge number of point temperatures are measured within the captured thermal image which is processed to form a thermal map of captured surface (Vadivambal *et al.,* 2010). It is reported that the thermal camera is capable of capturing images at a rate up to 60 images per second. It can sense temperature ranging from -20 to 1,500°C and the sensing range can be further increased by applying filters (Meola & Carlomagno 2004). The range of temperature to be sensed decides the type of detectors in thermal camera to be used which plays a vital role in thermal imaging system. The detectors used in food applications are generally of thermal detectors type where these detector elements gets heated up when infrared radiation falls on it by raising its temperature which will be measured by a temperature-dependent mechanism like thermoelectric voltage, resistance or pyroelectric voltage (Rogalski, 2003). Though thermal imaging system can detect entire wavelength of infrared radiations in electromagnetic spectrum at ambient temperature, only middle to far infrared (3-15 µm wavelength) are most preferred in food industry application. The thermal imaging devices used are of two types: Firstly, the un cooled thermal imaging device are most commonly used since they are less expensive and can operate under ambient temperature. Secondly, the cooled thermal imaging device which are very expensive and need extra supplements like cooling unit to maintain 0°C temperature during operation and are capable of sensing low temperature up to 0.1°C. In most of the food industry application the un cooled thermal imaging device are used. (Sierra Pacific Innovations, http://www.x20.org/thermal/thermal_weapon_sight.htm).

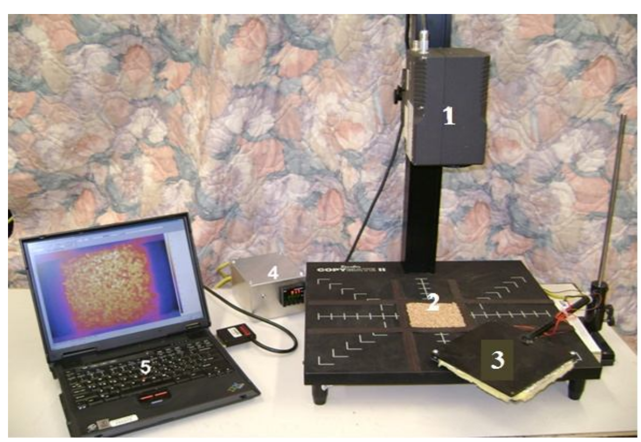

Fig.2: Thermal imaging system 1.Thermal camera, 2.Wheat sample, 3.Plate heater, 4.PID temperature controller, 5. Data acquisition system. (Chelladurai *et al.,* 2010)

Application of Thermal Imaging in Grain Storage

Thermal imaging has become potential tool for many applications in agriculture, starting from pre-harvesting operations like field nursery, irrigation scheduling, yield forecasting, harvesting, green houses, termite attack, farm machinery and post-harvest operations like maturity evaluation, bruise detection, detection of foreign bodies in food, determining heat distribution in cooking of food, and wood drying etc. Nonetheless, thermal imaging in grain storage plays a vital role in detection of sprout-damaged kernel, detection of foreign bodies in grains, detection of insects inside grain kernel, classification of grain, detection of fungal infection in stored grains, and detection of hot spots in grain bins etc.

Detection of Sprout-Damaged Kernel by Thermal Imaging

A sprouted kernel may be defined as one in which the germ end of grain is opened due to germination and exhibiting a sprout, or those in which the sprouts had been broken off leaving only the socket (Huang and Varriano-Marston, 1980). Thus sprouting will lead to harvest losses, reduced grain weight, loss of seed viability, and increase in amylase enzyme activity (Sorells *et al.,* 1989). The common methods used to determine the sprout-damaged kernels are visual inspection, falling number, and rapid viscoanalyzer. But the methods are either subjective or destructive and time consuming hence it cannot be used for online determination. Neethirajan *et al.* (2006) used soft X-ray image analysis for detecting sprouted wheat kernel mixed with healthy kernel. The classification accuracy were 90% and 95% for sprouted and healthy kernels, respectively using four-layer back propagation neural network classifier whereas 87% and 92% for sprouted and healthy kernels, respectively using four-layer back propagation statistical classifier. Singh *et al.* (2009) conducted a study to test the potential of near-infrared hyper spectral imaging for detection of sprouted and midge-damaged wheat kernels. The linear and quadratic discriminant statistical classifier by multivariate analysis gave maximum classification accuracy of 98.3% and 100% for classifying healthy and damaged kernels, respectively. Vadivambal *et al.,* 2010 carried out a study to detect sprouted-damaged wheat kernel from healthy kernels the thermal images of these kernels were taken and analysed using Mat lab. Classification of healthy and sprout-damaged kernel were done using Linear Discriminant Analysis (LDA), Quadratic Discriminant Analysis (QDA), and Artificial Neural Network (ANN). Authors found that the classification accuracy for LDA was 88.2% and 98.1%, for QDA it was 88.7% and 95.1%, and for ANN it was 99.4% and 91.7%, respectively, for healthy and sprout-damaged kernels. From the same study it was found that thermal imaging could be used online, i.e., as the grain flows through the conveyor, thermal images could be captured without the necessity for collecting samples. The use of NIR hyper spectral imaging showed good results but it is limited to single grain analysis and also offers less accurate results while soft x-ray is always risky for the operator.

Detection of Foreign Bodies in Grains by Thermal Imaging

Foreign bodies may be defined as any undesirable materials (dirt, stone, dead insects, rat excreta etc.) which are present in desired product (food grains). The high demand and expectations of consumer to get pure product free from these foreign materials have made food industry to invest on machineries for processing and inspection to ensure a good quality product for consumers. Several conventional methods like visual inspection which is time consuming, laborious and physical separation methods such as sieving, elutriation, sedimentation, screening, filtering, and gravity separation and advanced devices like metal detectors, X-ray machines and optical sensors were employed, but it was found that distinguishing foreign materials and the product depends on the response of the energy spectrum between the product and foreign body, hence there is no any device which can detect these type of contaminants regardless of size, shape and type Vadivambal and Jayas, (2010). Meinlschmidt and Margner, (2003) developed a thermal imaging setup to detect foreign materials like rotten nuts, hard shells, and stones in hazelnuts which are continuous moving over a belt conveyor. Using three image processing techniques (histogram analysis, texture analysis)an object-oriented algorithms for grains and online thermal imaging were developed. The physical behaviour of food and foreign materials, their shape and sound of the images were considered as detection parameters. Ginesu *et al.* (2004) used binarization, statistical and morphological analysis to find the feasibility of thermal imaging to discriminate the stones in almond, cardboard pieces in almond, wooden sticks in raisins, metal chips in almond and cardboard pieces in nuts as shown in Figure3. In this study mathematical morphology was specially designed to solve the problem of both food particles and foreign bodies having same grey level which was incapable with binarization and statistical approaches, the results obtained by morphological analysis gave promising results in different cases that were investigated.

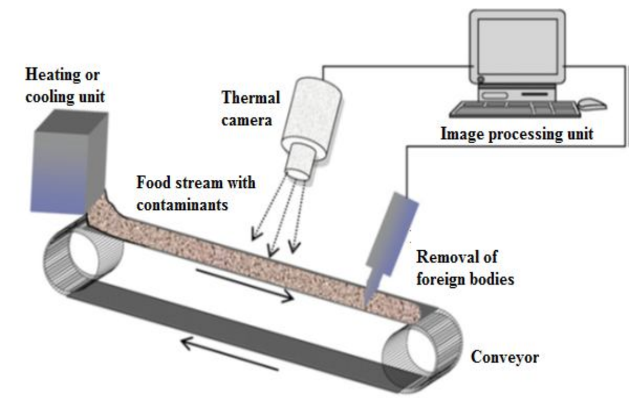

Fig. 3: Inspection of contaminants by thermal imaging *(Source: Ginesu et al., 2004)*

Detection of Insect Infestation inside Grain Kernel by Thermal Imaging

It is easier and better to prevent an insect infestation than to treat an established infestation. Therefore, the on time detection and tracing insect infestation in stored grains play a vital role in order to take necessary action for insect control. The general methods for this purpose preferred are:(i) determination of CO_2 production method which is not appropriate for high moisture grains (more than15%) since the CO_2 produced by the grains and other microorganisms will interact with the results (ii) ninhydrin reaction with amino acids of grain which is an destructive method (iii) floatation method which is not suitable for *Cryptolestes spp.* (iv) acoustic method which cannot detect eggs and pupae of insect, and (v) the X-ray method, which cannot detect larval development. However, all these methods are standardised by the International Standards Organisation (ISO) to find the hidden infestation in cereals and pulses methods have few limitations in applications. Few other methods still being used are insect traps for small scale stored grains and Berlese funnels method which is time consuming and cannot be used for all types of insect species (CFIA, 2008). Consequently, thermal imaging offers a new approach to detect the hidden infestation of all the life stages of insect (egg, pupae, larva and adult) inside the kernel by imaging the hot surface temperature of the grain created by respiration of insects (at all life stages) which produces heat more than that of heat produced by grains (Cofie-Agblor *et al.,* 1995a,b, 1996a,b: Damcevski *et al.,* 1998: Emekci *et al.,* 2002, 2004). Hagstrum *et al.* (1993) used acoustics to detect five species of grain beetles under varying temperature level. The *S. oryzae* and *T. castaneum* found first during more 10s intervals than *R. dominica, C. ferrugineus* and *O. surinamensis.* Data revealed that, when temperature was increased from 18 to 35ºC the number of sounds of *S. oryzae* increased but later decreased at higher temperature. Similarly, when temperature was increased from 17.5 to 30ºC the number of sounds of *R. dominica* increased but later it became constant at higher temperature. But in case of *T. castaneum* number of sounds was lowest at less than 25°C and then increased gradually as temperature increased. However, as mentioned earlier acoustics method fails to detect eggs and pupae stages of insect in grain kernel. Ken James and David Rice, (2002) investigated the use of thermal imaging cameras for detecting termites in floor, wall and ceiling spaces of home without damaging these structures. The hot spots regions containing termites inside the wooden structures were successfully identified by sensitive cameras. Manickavasagan *et al.* (2008) carried out a study to detect *Cryptolestes ferrugineus* infestation inside wheat kernels by thermal imaging. Results revealed that the overall classification accuracy obtained for a quadratic function was 83.5% and 77.7% for infested and un-infested kernels, and for a linear function was 77.6% and 83.0% for infested and un-infested kernels, respectively.

Classification of Grain by Thermal Imaging

Classification and grading of grains is done to improve the grain quality, acceptability, storage life, market value, and export potential to fetch high price. Consequently, the grading of grains was done by trained human inspector (visual inspection) which is a subjective method which leads to error in several circumstances (Majumdar and Jayas, 2000a). Hence a rapid method for online classification of grain into different classes was required and several efforts have been applied for online classification of grains using machine vision technology. Such as, Zayas *et al.* (1986)used grain factors kernel length, width, length ratio, tangent, sine, and length of arc of parabolic segment to categorize three classes of wheat from the USA (Hard Red Winter, Soft Red Winter, and Hard red spring) and achieved accuracy in the range of 77% to 85%. A morphological variation was used by Symons and Fulcher (1988a) to classify three eastern Canadian wheat classes which offered classification accuracy in the range of 64% to 100%. Myers and Edsall, (1989) used size and shape features to categorize five Australian wheat varieties and achieved a classification accuracy in the range of 44% to 96%, respectively. Majumdar and Jayas, (2000) developed digital image analysis algorithms to classify bulk samples of Canada Western Amber Durum (CWAD) wheat, Canada Western Red Spring (CWRS) wheat, barley, oats, and rye cereal grains based on their colour and textural features. Various combinations of grey scales were tried, out of which red colour band gave 100% classification accuracy for cereals grains that were investigated. Mahesh *et al.* (2008) conducted a study to test the feasibility of NIR Hyper spectral Imaging to differentiate three different Canadian wheat classes by scanning the samples at 10 nm intervals in the wavelength region of 960–1700 nm. Both the statistical classifier and artificial neural network (ANN) classifier were used to differentiate the samples, results from Linear discriminant statistical classifier by leave-one-out cross-validation method showed 100% classification accuracy for two red wheat classes and one white wheat class. While linear discriminant artificial neural network (ANN) classifier showed more than94% for the other five different wheat classes investigated. Likewise, the Quadratic discriminant with a leave-one-out cross-validation method gave classification of more than86% for all wheat classes investigated. Neuman *et al.* (2009) investigated digital image analysis discriminate wheat class and variety. The system had classification accuracy ranging from 15 to 96% to discriminate the varieties within classes. Manickavasagan *et al.* (2010) presented a new approach to categorize eight western Canadian wheat classes by using thermal imaging system and results showed an overall classification of an eight-class model using bootstrap and leave-one-out validation methods were 76%, 87%, 79%, and 95%, and 64%, 87%, 77%, and 91% for red-class model (four classes), white-class model (four classes), and pair wise (two-class model) comparisons, respectively. Mahesh *et al.* (2010) reported another study to classify four western Canadian wheat (13% moisture content) harvested during 2007, 2008, and 2009 crop years and collected from various growing locations by applying NIR hyper spectral Imaging. The linear and quadratic discriminant statistical classifiers offered 95.4 and 92.3% classification, respectively when the samples scanned with 10 nm intervals between the NIR wavelengths of 1260-1380 nm. Even though, the NIR Hyper spectral imaging have a potential in classification of grains but results obtained will be less accurate and it is time consuming method, since only single grain can be analysed at a time. The grain classification using thermal imaging is found very limited even though it is having potential to offer high classification accuracy unlike other method. Hence specific methodology and procedures need to be developed for different varieties and classes which are alike and hard to differentiate by visual inspection. Further, research studies are need to be carried out to study the performance of developed systems for classification of heterogeneous mixture of grains, defect grain, same variety with different grades, foreign bodies and samples with varying kernel sizes and quality within a class.

Detection of Fungal Infection in Stored Grains by Thermal Imaging

Fungus in stored grain is the most difficult enemy to be recognized and to be alive they feed on stored products. The presence of fungus in grains results in the breakdown of the product tissue, development of bad taste and off-odour in grains, loss in nutritive value and seed viability. Fungus develop best in a warm and humid atmosphere, a dry atmosphere can prevent the germination of fungal spores and thus the development of fungi. When the air is warm, it holds certain amount of water while it gives off this water when it gets cooled which will be condensed to form dew, on other hand this dew make the grain wet inducing cracks and mould development. Subsequently, the developed fungus and insects will starts respiring along with the grains producing heat which leads to hot spots formation in areas of the grain where most fungus and insect activities are occurring. The fungal infection in stored grain is mainly caused by *Aspergillus spp.* and *Penicillium spp* (Wallace and Sinha, 1962).The growth of fungus was maximum at 30-35°C temperature and more than15% moisture content (Muir and white, 2001). Generally fungal detection in stored grain is done by plate agar method which requires long incubation period and can detect only few species of fungal strains (Lacey *et al.,* 1980) and other methods like high performance liquid chromatography (HPLC), gas chromatography and mass spectroscopy (GC-MS), sensory analysis and electronic noses **(**Lin and Cousin, 1985; Schnurer *et al.,* 1999; Smith *et al.,* 1994; Keshri and Magan, 2000), all these methods uses the volatiles produced by fungus to detect the fungal activities which requires long observation time period. Hence an advanced techniques such as near-infrared transmittance (NIRT), near-infrared reflectance (NIRR) spectroscopy (Pearson *et al.,* 2001) and soft X-ray imaging (Singh *et al.,* 2007) was introduced to detect fungal infection in stored maize and wheat kernels, the results from NIRT and NIRR technique obtained were found to be impressive in classifying scab damaged and healthy kernel but failed to classify scab damaged, mould damaged and un-infested kernels. Hence author stated that NIR reflectance spectroscopy can be used as a potential tool in wheat grading and commercial sorting. The results of X-ray imaging were remarkable in detecting *Aspergillus spp.* and *Penicillium spp*. but the method needs a well-trained operator and not suitable for online detection since it is a single kernel analysis. Hence, there is a need for developing a simple, reliable and real-time fungal detection method in bulk grain to overcome above drawbacks. Narvankar, (2009) investigated the potential of soft X-ray imaging to detect fungal (*Aspergillus niger*, *A. glaucus*, and *Penicillium* spp.) infection in wheat.

The linear, quadratic, and statistical discriminant classifiers and back-propagation neural network (BPNN) classifier were used in which the statistical discriminant classifier offered 92.2 to 98.9% and more than 82% accuracy was obtained by neural network classifiers for fungal-infected wheat kernels. Chelladurai *et al.* (2010) published the results of detecting the fungal infection in stored wheat using thermal imaging. The authors investigated the feasibility of thermal imaging system to detect the wheat grains infected by *Aspergillus spp.* and *Penicillium spp.* and results concluded that, maximum classification accuracy of 100% for healthy samples and more than97% and 96% for infected samples were obtained from Pair-wise LDA and QDA classification models, respectively. Whereas very low classification were obtained when four-way LDA and QDA classification models were used, due to changes in the temperature features between wheat kernels infected with different fungi species was very little. Nevertheless, use of thermal imaging for fungal detection is a promising alternate method which is simple to operate and can be used in online inspection, hence there is still research thrust required to improve the performance of system to differentiate the fungal species which develops mycotoxins, which could be possible by combining the thermal imaging with optical imaging by considering the colour changes caused by different fungal species.

Detection of Hot Spots in Grain Bin by Thermal Imaging

Hot spots are high temperature regions which are created by respiration of fungi, insect or sometime stored grains itself, which initiates the spoilage of grains. Reasons for hotspot development are loading of high moisture grains over dry grain inside storage bin, entry of water through leaks and holes, entry of snow through ducts, rising of moisture within grain bulk due to respiration of insect or grain and moisture rising through cracked floor. Hot spots, originating from either fungal or insect activity, may develop during the late fall, particularly in non-aerated grains. Wilkins, (1983) revealed that heating by fungi was initiated in winter primarily by the activity of low temperature *Penicillium* species growing in a 4 month old grain pocket of -5°C to +8°C and 18.5% to 21.8% moisture content. The hot spot reached a maximum of 64°C in 3 months, and cooled in 2 weeks. White, (2001) suggested that grain bulk in storage structures should be inspected at least once in week at a depth of less than 0.5m interval to detect the hot spots. The common methods of temperature measurement is performed by using large numbers of thermocouples, thermometers, thermistors, resistant temperature detectors installed at various locations of bin. These instruments will measure the temperature only at specific points if the instruments are in contact with the object. Therefore to accomplish this large number of temperatures sensing devices should be installed throughout the grain bulk, in case the storage bin is too large it would become even more complicated to find hot spots using these devices which measures temperature only at specific points. Therefore thermal imaging is an exceptional alternate method which can sense the temperature distribution across a specific area of interest by capturing a thermal image using infrared camera without making contact with grain sample. Manickavasagan *et al.* (2006) was first to study a new approach to detect hot spots in bulk grain (barley) stored in silo by using thermal imaging. Artificial heat source was placed at various locations inside grain bulk and maintained different temperature at each locations. When outer surface of silo wall and top surface of the grain surface were thermally imaged with a distance of 5m between camera and bin, hot spot was detected with thermal images of silo wall and grain bulk when it was placed at 0.3m far from inner silo wall, and 0.3m depth below the grain surface, respectively. This study also reported that thermal imaging is strongly affected by environmental factors like sun radiation, radiation reflected from surfaces of nearby objects inside laboratory, wind velocity around thermal imaging system, temperature of ambient air, and moisture content of the grain. In same study authors found that painting the outer bin surface with high emissivity paint reduced solar heating by warm climate. Vendt *et al.* (2011) carried out a study to determine the effect of environmental conditions on performance of thermal imagers and proved that the performance of the thermal imagers was not significantly affected by the target temperature (-15ºC to 120 ºC with uncertainty limits of 0.5 ºC) in his experimental setup, which consist of climatic chamber and flat black body temperature controller. However, study also indicated that experimental setup can be further investigated to test the effects on the thermal imager's performance.

Research Needs

Thermal imaging has numerous potential applications in food grain industry both to prevent the grain loss and to preserve the grains safely by forecasting the future problems to the grains ensuring to take timely action against those factors affecting the grain storage. Nevertheless, application will become even more wide spread in grain industry if cheaper infrared detectors (thermal camera) are developed. In addition to this the system has to overcome a number of shortcomings such as thermal imaging performance should be improved for its usage in online classification of grains. Since the system operation speed is slow, when dealing the large scale classification of grains there is necessary to conduct a study to enhance the speed of operation. The image processing system performance should be improved to categorise the sample containing mixture of different variety of grains, grains with different moisture content, foreign materials and grains with different sizes. Detection of insect eggs over surface of the grain before it hatches will help to reduce the most of insect infestation in stored grains thus prevent loss of grains in huge margin. Thermal imaging fails to differentiate the mycotoxins producing fungal species with other species infecting the grain hence this would be challenging study to identify those species before they create lethal effect in grains. When dealing with detection of hot spot in middle of the grain bulk stored in large silo or bin storage structure tosses another challenging task, hence a study should be conducted to find a way for detecting hot spots developed in middle of storage.

Good results have obtained from imaging the drying of wood surface by infrared thermal imaging, hence similar studies can be conducted to explore the thermal imaging in grain drying to achieve uniform drying. Few studies have reported that the performance of imaging system is affected by many environmental conditions like temperature, wind, solar radiation, cold weather and moisture content. Therefore, developing an imaging system which can tolerate all these environmental effects need to be done to improve the accuracy of measurements. Thermal imaging is non-contact and non-destructive method of temperature measurement tool which has number of applications in grain industry. Even though, the advanced technologies such as NIR spectrometry, soft X-ray methods and acoustics method presented good results for tested samples, these methods fails to sense temperature changes, detect the hot spots in bins, cannot find larval insect stage inside kernel, and use of X-ray is threat for the operator. Hence, further studies need to be conducted to improve the thermal imaging system which could offer alternate solution for these drawbacks. In addition to this, thermal imaging is still being used under lab or experimental stages, hence further research should be focused to produce low cost thermal camera to explore the potential capabilities of this tool for facilitating to adopt in large scale industrial application.

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