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Research paper

Sensing Technologies used for Monitoring and Detecting Insect Infestation in Stored Grain

Rekha Kaushik[1]*, Jyoti Singhai[2],

[1]*Department of Electronics and Communication Engineering, MANIT, Bhopal, M.P., India*
[2]*Department of Electronics and Communication Engineering, MANIT, Bhopal, M.P., India*
**Corresponding author E-mail: rekhakaushik28@gmail.com*

Abstract

In India, the production of grain has been steadily increasing. Improper storage of grain results in higher losses in terms of quality as well as quantity. Contamination of grain occurs due to insects and micro-organisms present in it. Their presence and growth highly depends on environmental factors. When grain gets infested, volatile compounds get accumulated and release odour. The rapid growth of sensing technology makes the early and accurate detection of insects/fungi more promising. This paper discusses about different kinds of sensing technologies such as environmental sensing, acoustic sensing, odour sensing and image sensing, their working, challenges and issues, advantages and limitations. Future trends of using sensing technology are also discussed.

Keywords: *Acoustic sensing; E-nose; Insect infestation; Sensors; Stored grain*

1. Introduction

India is an agricultural country where GDP is mainly based on its agro products. Post-harvest stored grain loss is in between 7-15% due to inapt storage. During storage quantitative as well as qualitative losses occur due to insects present in grain. The major economic loss caused by grain infesting insects is not always the actual material they consume, but also the grain gets contaminated by their waste. This makes the food unfit for human consumption. Insects in stored grain are mainly divided into two categories namely primary and secondary storage insect according to their feeding habits [1]. Insects that damage sound grains are associated with primary storage. Main insects found in India are Rice weevil (Sitophilus oryzae), Khapra beetle, Lesser grain borer (R. Dominica) etc. These insects can be internal and external feeders. Those insects that damage broken or already damaged grain are associated with secondary storage insects. Rust red flour beetle (Tribolium Casteneum), Rice moth, Long headed flour beetle are main insects found in stored grain in India. The life cycle of granary insects can consist of four stages namely eggs, larvae, pupa and adults. Different stages of insects cause different level of contamination in stored grain. Existing methods [2][3] for the detection and monitoring of stored grain insects includes visual inspection, carbon dioxide measurement, trapping, sampling, uric acid measurement and near-infrared spectroscopy. However, timely detection of insects responsible for the contamination of grain with these methods is very challenging. The cost of collecting data for the early detection of contamination of grain using current methods are labor intensive, expensive, time consuming and imprecise.

Sensing technology is currently an automated, remote and promising technique. It is used for monitoring the quality of grain and for detecting insect infestation in stored grain. It allows faster deployment and installation capabilities. To monitor and detect contamination in grain, environmental parameters sensing, acoustic sensing, odour E-nose sensing, image sensing techniques can be applied. The data obtained from these techniques are used to predict contamination of grain or to classify insects. Here data processing is an important step. It can be done using methods like neural network, machine learning algorithm, statistical analysis, pattern recognition etc. Sensor data can be used for real time monitoring of insects in stored grain bulk using sensor network. Various types of sensors and their applications are identified for their deployment in grain storage [4].

The objectives of this paper are (i) to discuss and integrate the parameters that deteriorate the quality of stored grain (ii) to discuss types of sensing technologies such as environment sensing, acoustic sensing, odour sensing and image sensing for the early detection and monitoring of insect infestation (iii) to discuss issues related to design, working, deployment, advantages and limitations of sensors and sensing technologies.

2. Environment Sensing

The most important environmental factors to be observed for successful storage of grain and maintaining its quality are moisture content, temperature, CO_2, and O_2. These factors affect the mortality of adult and larva insects and micro-organisms in it. The survival and reproduction of these insects depend on temperature and moisture level. When grain spoils, heat and moisture are produced due to insects feeding and respiration. Excess of CO_2 in grain indicates incipient spoilage of stored grain.

2.1 Environmental parameters affecting storage

Monitoring changes in temperature is a traditional method used with the store grain mass to monitor quality of grain. Temperature above 15^0C is an ideal condition for insect growth and reproduction, whereas 25 to 30^{0}C are suitable for mold growth [5]. With lower temperature, the metabolic rate of fungi and insect decreases. Temperature increases as insects produce heat. Also, the grain when deteriorated due to self-heating causes increase in temperature. Measurement of temperature in different storage can be done by using equipments like bin thermometer, thermocouples, temperature cables, temperature sensors [6]. Among all measures of temperature sensor is a fast, less expensive and accurate method for measuring temperature. The presence of insect is not detectable by temperature sensor alone as insect can develop at close range of temperature.

High moisture content present in grain is the main cause of insect infestation, loss of freshness and odour development in grain mass. High moisture content in grain of over 12% causes damage to the seeds because it promotes diseases. At 13.5 to 15% moisture levels some fungal spores begin to grow, other species of fungi require 16-23%. Aerobic bacteria require 20% to grow. Grain spoilage caused by molds, mites, insects can be detected by measuring CO_2 concentration in the intergranular air. As these organisms respire, the level of CO_2 concentration changes and can be observed using sensors. CO_2 concentrations of 600 to 1,500 ppm indicate onset of mold growth. Concentrations of 1,500 to 4,000 ppm and beyond clearly indicate severe mold infection or stored-product insect infestation.

Techniques to cope up with the problem of incipient deterioration related to environment in post harvest stored grain are i) controlling the environmental factors by designing special silos/warehouses/bins ii) Aeration iii) drying etc. These techniques can be applied to prevent or discourage the growth of micro-organism and insects. Before applying any of the technique, if owner have accurate values of individual environmental factors then it would be easier to apply appropriate techniques to improve grain quality. An environmental monitoring sensing system is an appropriate method to monitor the stored grain on real time basis.

2.2 Types of sensors

Lots of sensors are available in market to monitor environmental parameters. Among these, existing work mainly uses sensors such as LM35 for monitoring temperature, DHT22, SHT21, SY-HS-220 for monitoring temperature as well as humidity in stored grain [5,7]. Rethorpe moisture sensor measures moisture content. Currently available sensor for measuring CO_2 concentration are Metal oxide sensor (MOS) such as MQ7 [5], optical sensors like Non-dispersive infrared detector (NDIR), electrochemical sensors, polymer based sensors etc[8]. Usage of these sensors depends upon application and requirement of the user. These sensors can be distinguished on following parameters: the lifespan of MOS is long but its cost and sensitivity is low. The energy consumption of electrochemical sensor is low as compared to MOS and NDIR sensor. Optical sensors are large in size. Development of application specific sensor having characteristics like accuracy, reliability, data gathering, zero cross sensitivity, easy to use for non technical users, power saving is still a challenge. The data so collected gives information of atmospheric parameters of grain after processing it. With wireless technology, information can be accessed via computer, laptop or Smartphone. Alerts can also be generated for managers to receive real time data of silos or warehouses.

Some of the issues while using sensors in a large grain mass are deployment and design of sensor to get accurate results. Simultaneous monitoring of environmental parameters requires specific hardware design. Data security and privacy is another issue. Calibration of sensor is another issue as the sensitivity of a sensor gets affected by other environmental parameters. Data collection and its analysis, logging data are other points which have to be taken into consideration while using sensor network.

2.3 Existing work

Following are the work done by different authors in the field of monitoring environmental parameters to monitor quality of stored grain. Harein and Press (1968)[9] shows that the mortality of insects increases with the decrease in O_2 concentration, it increases in CO_2 concentration. The insect mortality also increases with increase in temperature (15.6-37.8^o C). In [5] author monitors CO_2 level in silo containing maize for eight months. It is shown that CO_2 sensors can be effectively used for the early detection of spoilage and growth of insects, molds and mycotoxins by correlating with CO2 levels. Researchers are still developing inexpensive and highly accurate CO2 sensor. In [10], author developed CO_2 sensor using PABA conducting polymer and it dynamically detected up to 2455 ppm of CO_2 levels in the grain bulk.

Instead of silo, periodic monitoring of CO_2 is studied for different moisture content for detecting increases in biological activity and conservation problem in silo bags of wheat and soyabean. It is observed that CO_2 concentration increases with increase in moisture content [11]. In [12], Relative Humidity, Temperature, and CO_2 sensors are simultaneously used on wet grain mass (wheat) storage to improve storage monitoring during aeration. In [13], design of a distributed wireless sensor network to determine moisture content in bulk grain stored in silos is discussed. In this paper sensor calibration is done using saturated salt solution. In [7], author proposed a schematic diagram of a modern in-silo drying and aeration system which consist of various sensors for monitoring temperature, moisture content and CO_2. This paper compares various sensors and discusses their advantages too.

Limitations of using environment sensing technique for stored grain are: a well designed silo/warehouse is required. This technique is not successful with very small grain mass. This technique is unable to detect insects, type of insects and their stages present in grain which are responsible for infestation of grain. However, deterioration in grain may occur due to mold or insects present before it is detected that there is rise in temperature. Also, limited sensing range of temperature sensor may sometimes not detect hotspots.

3. Acoustic Sensing

Acoustic sensing is used in several areas related to agriculture (crops, trees) and safety of food products (grains, fresh fruit, dry fruits etc) to monitor the insects present in them. This technology also meets the requirement of several researchers, entomologist and pest manager for rapid, automated, effective and inexpensive detection of hidden insects' infestation in stored grain. Acoustic sensor uses sounds/vibrations generated by insects while moving, flying, and feeding to detect them. Hidden insects within the grain can be detected acoustically by amplifying and filtering the sound generated by them. This technique can be used to detect the presence or absence of insects, larva, estimating the population density of insects inside the grain mass so that the level of infestation can be judged.

3.1 Types of acoustic sensor

There are several types of acoustic sensors used for detecting insects present in grain. It depends upon several factors such as frequency range of sensor, substrate structure, insect type and its size. Microphones are the sensors useful for sensing airborne signals but most of the existing work uses piezoelectric sensors [14][15] as they are more sensitive to sound signals generated by insects when kept in direct contact with them. There are several commercially available sensors like guitar pickups, geophones, and accelerometers which contain piezoelectric sensors. This sensor uses different kinds of amplifiers to increase signal amplitudes efficiently for data analysis and interpretation. Another sensor is ultrasonic sensor which can detect nearby insects with background noise between signals from 20 to 200 kHz [14]. In recent years, bioacoustic sensors have been used for the same purpose. It combines the applicability of signal processing and machine learning techniques [16].

While using acoustic sensors following issues should be considered for accurate detection and monitoring of insects in a grain mass such as number of sensors required, exact location to place them in grain mass, analysis of data generated by sensors. Apart from these issues, other problems that should be taken into consideration are i) while detecting insects in silos acoustic signal attenuates as the mean spectrum of signals produced by targeted insects is different in different grain and it changes with distance from insect position. ii) Separation and reduction of background noise from the sound produced by insect(s) generated while grain settling. iii) Effect of environmental condition on sound produced by insect. iv) Discrimination of acoustic signal produced by adult and larvae insect as well as from target insect to non target insects.

3.2 Existing work

The need to monitor hidden insects and for the automatic acquisition of data gave rise to various methods such as1) development of sound insulation chambers such as construction of Muffle box[17] to discriminate the sound of insects with background sound generated while grain settling. Muffle box is capable of discriminating larva sound pulses with background noise. The limitation of using Muffle box is its bulkiness. 2) Development of probes (like EWD) to detect the insects inside the grain [9]. Probes with PC assisted decision support system can be used within the grain samples or even directly in grain bulk. The limitation of acoustic probes designed for estimating insect population was low sensitivity. 3) An automated system in which sensor network and signal processing methods greatly increased detection reliability to distinguish insect species. In order to predict the presence of insects, data processing is needed.

Initially, acoustic detection of stored product insects starts with the detection of adult insect. Hagstrum and Flinn in 1993 reported that the smaller C. ferrugineus and O. surinamensis produced fewer acoustic emissions and were more difficult to detect compared with the relatively large S. oryzae and Tribolium castaneum (Herbst)[18]. In 1996, it is shown that signal produced by s.oryzae is only 23dB[15]. Hickling et al.[19] shows that type of grain is an important factor that affect the intensity of sounds produced by insect. It is shown that sound is transmitted over longer distances in grains with a larger inter-kernel spacing, such as maize. In [20], it is shown that number of sounds produced by S. oryzae, R. dominica and Sitotroga cerealella (Olivier) varied significantly among different grain types (rice, corn or wheat). In 2008, hill detects 218 species in 12 insect orders.

All the above work mainly focuses on detection of adult insects but not larva. Inspite, the larva feed unseen inside the kernels of grain and hence infestations often remain undetected until considerable damage has occurred. Several types of models used for data processing are obtained from acoustic sensors. A time delay neural network with feature extraction was successfully trained to distinguish different classes of sound which include adult sound, larva sound, grain settling sound and external sound occur in grain silos [21]. Sitophilus granius(L.), Tribolium confusum and R. dominica larvae are distinguished from each other in grain based on their spectral features in a study done by Schwab and Degoul in 2005[22]. Another feature that is used to discriminate the larva signals is temporal pattern which usually contains brusts or groups of impulses separated by intervals of 250ms [23]. Kiobia at al[2015] detected larval sound of S. Oryzae impulses frequently within 25 cm from the pouch contacting larvae in maize. Numerous sounds of 4 different types were detected over a range of frequencies extending to 7 kHz[24].

Mankin et al[15] provides a very effective study which shows the progress made within current century in the development of acoustic devices and applications for the insect detection in crops, grain and soil. Eliopoulos et al[25] in 2016 evaluates the potential of bioacoustics to estimate population density of insect inside the stored grain mass. Piezoelectric sensor and a portable acoustic emission amplifier are used for storing vibration signals of insect. In this paper, different insects are chosen based on their different attributes like their body size, walking and feeding behavior on various types of grains. Multiple classifiers were used to evaluate the accuracy of bioacoustics on predicting the pest density given per minute counts of vibration pulses. The linear regression model is used for this purpose. About 68% accuracy is achieved in estimating population density of insects.

Although, acoustic technique is very promising method but this technique has some limitation too. The main limitation of acoustic technique is that the initial stages of insects like egg and pupa, dead insects within the grain cannot be detected which also have severe effect on human health. The acoustic signals of insects are sometimes disturbed by environmental noises and are often weak and are easily drowned by other noises.

4. Odour sensing

The off-odour of grain is a useful criterion for classifying grain quality. Smelling odour with the human nose is the traditional method to evaluate the quality of grain. Based on odour, grades to the grain had been given such as good (fresh), musty, moldy, insect, and burnt [26]. The contaminated grain releases volatile compounds which may cause severe health hazard as the spores can be inhaled by the inspector. To overcome this problem, an intelligent technique such as electronic-nose (e-nose) has being used for the detection of odour released by grain. E-nose is an electronic device consisting of an array of sensors and software used for data processing and pattern recognition to recognize odour. It receives attention in various application areas including agriculture due to advancement in sensor technology and design, software innovations and improvements. Human nose can detect a limited range of odour but e-nose has an advantage of detecting odour which cannot be possibly detected by human nose as well.

4.1 Types of E-nose

Some of the E-noses that are commercially available and most widely used for the classification of grain use metal oxide semiconductor (MOS) sensors or MOSFET sensors. Most of the existing work uses models like PEN2, PEN3, FOX3000, Cyranose 320 uses MOS sensors. Other models of e-nose may have electrochemical sensor, conducting polymer sensor, optical sensors, and Quartz crystal microbalance sensors [27]. To classify the odour, several classification algorithms and regression are applied on the data such as Artificial Neural Network (ANN), support vector machine (SVM), Linear discriminate analysis(LDA), k-mean clustering analysis, fuzzy c-mean clustering, BPNN, principal component analysis(PCA) etc.

4.2 Existing work

Use of E-nose for detecting insect infestation in stored grain is slowly expanding. Stetter et al. in 1993[28], shows 83% accuracy when wheat samples were successfully classified using E-nose. In this work, author uses e-nose which consists of electrochemical gas sensor combined with pattern recognition methods. T.borjesson et al in 1996[22] uses e-nose to classify grain samples of wheat, barley and oats. They used sensor like MOSFET, SnO_2, infrared detector for CO_2 and ANN for data processing. This work has been able to correctly classify different categories of grain upto 91%. Jie Hu (2006) [30] used E-nose technology to detect insect damage in rice crop. Degrees of insect damage could be detected and differentiated. It was observed that the longer the infestation time, the better E-nose was able to identify infested grain. Zhang and Wang (2007) [31] uses PEN2 e-nose with ten different MOS sensors to successfully discriminate among wheat samples of different ages. It is shown that fifteen percent of insect damage could be determined by applying PCA to the signal of optimized sensor array. BO Zhou in 2011[32] uses PEN2 device to predict the number of infesting insect in rice samples. Different numbers of insects such as 1, 5, 10 and 40 are placed in different samples. Statistical technique such as PCA, LDA, PCR, PLS and BPNN were used to analyze the data obtained. It is analyzed that BPNN had best results on predicting insects when comparison done on two parameters stored time(ST) and different number of infesting insect(NI).

J. Wu in 2013[33] uses AlphaMOS Fox3000 e-nose to detect insects like Red Flour Beetle (RFB) and Rusty Grain Beetle(RGB). Results shows that with low moisture content (14% and 16%), E-nose is able to detect infestation level of grain with 20 RFB but not able to detect RGB. It can also differentiate infestation level with 1 RFB and 20 RFB. E-nose got affected with moisture content of grain. With higher moisture content, e-nose is unable to detect and discriminate insect(s) volatile. Sai xu et al [34] uses PEN3 E-nose to predict the duration and prevalence of insect (red flour beetle) infestation in stored rice. To show the result, different infestation degree and time duration are considered. Experimental results shows that LDA, K-Mean and Fuzzy c-mean clustering are able to classify the infestation but FCM more correctly predicted the infestation duration during 4 different degree of damage treatment than k-means.

Other than insects, fungi are also responsible for contamination of stored grain. With the help of e-nose fungi can also be detected. In [35], the fungal species studied are Eurotium amstelodami, E. chevalieri, E. herbariorum, E. rubrum, a Penicillium species and Wallemia sebi. In [36], grain mould prediction has been successfully done with accuracy rate of 93.75% using probabilistic neural network and e-nose.

An improvement in selectivity and sensitivity in e-nose is still needed to identify gas samples and VOC with high efficiency. The limitations of e-nose are: they need training and practice for proper operation of algorithms. E-nose output data and results may vary due to humidity and temperature. They are very expensive.

4. Image sensing

Above sensing technologies are unable to detect the exact location of infestation caused by insects in stored grain. This limitation can be overcome by using image sensing technology. Image sensor is a wireless autonomous monitoring system which periodically captures images of the trap contents and sends them remotely to a control station. Sent images are then used for determination of the number of insects found at each trap. Based on insect population number, a grain storekeeper can plan when to start grain protection (example: fumigation etc) and in which particular area. From this method, one can judge the type of insect as well as insect population.

In this technology, images of insects get acquired. The data of images corresponding to time, GPS location is transmitted to a control system for further processing to detect or classify insects.

A few measures to take care while using this technology are i) lightning condition in real time environment ii) image capture is with or without constraints. If so, how to remove constraints? Example, removing background image with target image iii) Number of classifier used iv) how many classes or data is available to evaluate the performance v) method to evaluate the performance.

A comprehensive study is done in [38] on image based insect classification. This study discussed on type of images, how to extract feature with different methods and classification methods with their issues and database. Insect's image capturing and processing in protecting crops is discussed. In [37], author uses an automated sensing technology for monitoring insect traps based on low cost image sensors. Wireless sensor platform is consisting of Imote 2 developed be Intel MEMSIC, CMUcam3 and Mesheye. Selection of camera depends on its high resolution, low cast, and low power. All work done is performed in open environment as camera needs sufficient light to capture images. With stored grain in closed place this becomes a limitation.

5. Conclusion

This work provides a comprehensive study on the sensing technologies used to monitor the quality of stored grain. To observe the quality of stored grain and to detect insects present in it responsible for the contamination of grain, three technologies are discussed including environment sensing, acoustic sensing and odour sensing through e-nose. The potential of sensors, their types, issues and challenges of using them is discussed. Sensing technology provide an automated, rapid, promising, cost-effective and accurate method to monitor the quality of grain.

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